



PHD

Non Destructive Testing of Drystone Walls

Warren, Laura

Award date:
2018

Awarding institution:
University of Bath

[Link to publication](#)

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

Copyright of this thesis rests with the author. Access is subject to the above licence, if given. If no licence is specified above, original content in this thesis is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC-ND 4.0) Licence (<https://creativecommons.org/licenses/by-nc-nd/4.0/>). Any third-party copyright material present remains the property of its respective owner(s) and is licensed under its existing terms.

Take down policy

If you consider content within Bath's Research Portal to be in breach of UK law, please contact: openaccess@bath.ac.uk with the details. Your claim will be investigated and, where appropriate, the item will be removed from public view as soon as possible.

Non Destructive Testing of Drystone Walls

Submitted by

Laura Warren

For the degree of Doctor of Philosophy

University of Bath

Department of Architecture and Civil Engineering

May 2018

COPYRIGHT

Attention is drawn to the fact that copyright of this thesis rests with the author. A copy of this thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with the author and that they must not copy it or use material from it except as permitted by law or with the consent of the author. This thesis may be made available for consultation within the University Library and may be photocopied or lent to other libraries for the purposes of consultation.

Signature of Author.....

(Laura Warren)

Acknowledgments

This thesis was carried out in the department of Architecture and Civil engineering between 2011 and 2015. The author would like to thank the department for allowing this thesis to be carried out as it not as was originally intended!

The author would also like to thank Shane Donohue who was initially supervising this project for his continued support throughout the study even though he unfortunately moved on from the University of Bath. Thanks also to Paul McCombie who initially was second supervisor but stepped up when Shane left to become the lead supervisor. Paul has provided many an idea and continued moral support in all aspects of PhD life even those not relating to the study. Also thanks to Kevin Briggs who stepped in as second supervisor on Shane's departure.

A massive thanks must also go to those who enabled this thesis to happen by providing information and access to these drystone structures. Firstly to the members of the Drystone Walling Association, in particular the members of the south west branch with a special mention to Nigel Chivers and Phil Smith, who arranged a number of visits to look at walls under his construction and imparted a vast amount of wallers knowledge through conversation. Many thanks to them as well for inviting me to talk at their AGM and the general interest within the walling community in the research being carried out. Many thanks also to the Festinogg railway for a very enjoyable two days on our own private train looking at their embankment walls and again imparting a great amount of knowledge. Special thanks to Graham Cole who arranged this for us as well as took the time along with 2 other members of the railway team to show us around. Thanks also to the wallers in southern France, Thomas Brasseur and Bruno Durand, who took time from their work to show us around and discuss the French walling techniques with

us during our visit in September 2013. Thanks also to Cathie O'Neil who helped to arrange this.

Thanks also goes to Gloucester and Cornwall Highways departments for allowing us access to their records and for discussing how they deal with the issues of drystone retaining walls and their assessment.

For their help with the GPR work thanks also goes to Dr S.R. Pennock and Dr C.H.J. Jenks from the University of Bath Electrical Engineering Department, who provided the equipment as well as processing the data from this to produce visual images.

On a more personal note thanks goes to my parents for their continued support and joining me on at least two excursions to Cornwall to look at walls here! Thanks also my other half Jethro who has not only proof read the majority of this report (and made my English far better than it was!) but has also encouraged me to keep going when times are hard and has even been mad enough to propose! Also thanks to all my friends both at university and at home along with those mentioned above who have listened to the tears, tantrums and triumphs of the past few years.

Abstract

Drystone structures have been widely used throughout the UK and other parts of the world for hundreds of years. Many of these structures are still in use today with many of the existing drystone structures within the UK being over 100 years old.

Drystone construction techniques have formed over the years to make best use of stone properties, enabling these structures to resist the loadings upon them. Typical construction styles can often be attributed to certain types of stone, each with their own characteristics. Within these styles subtle variations can be found, often specific to an area, which work best with the properties of the local stone types. The predominant use of drystone structures also influences the way in which they are built in a particular area. This has been demonstrated in comparing the construction within the UK to that in the Cevennes area of France.

The existing retaining wall stock needs to be assessed by the authorities that manage them. Many of these walls support highways and infrastructure, so adequate assessment and monitoring of these structures is vital to ensuring these services are maintained. Assessment of a structure mainly relies on engineering judgement, often with little to no prior knowledge of its behaviour or details of its construction.

This thesis studies a wide number of walls both in the UK and France to understand qualitatively the construction of these structures, and how the material used together with local practise influences the overall construction. This in turn influences the ways in which loads are resisted by each of the main construction types.

Following from this it goes on to look at practical ways in which assessment could be aided by identifying features within a wall that are known to assist or hinder a wall's performance. The main technique developed for this is thermal imaging. Through

practical studies and thermal modelling, a number of proposals have been put forward regarding the best times of day for using this technique. The type of features that may be identified has also been examined and discussed.

Table of Contents

Acknowledgements.....	1
Abstract.....	3
Table of Contents.....	5
List of Figures.....	7
List of Tables.....	10
Chapter 1: Introduction	11
1.1 Introduction.....	11
1.2 Walling Construction.....	12
1.3 Aims and Objectives of Study.....	16
1.4 Thesis Layout.....	18
Chapter 2: General Research on Drystone Retaining Wall.....	19
2.1 Introduction.....	19
2.2 Full Scale Tests – Burgoyne.....	20
2.3 Summary of Analytical Work Based on Burgoyne.....	22
2.4 Experimental and Analytical Work by Villemus (2004).....	27
2.5 Experimental and Analytical Work by Colas (2009).....	30
2.6 Experimental Work by Mundell (2009).....	31
2.7 Drystone Modelling.....	36
2.8 Practical Walling Advise for Assessment.....	41
2.9 Conclusion.....	42
Chapter 3: Walling Studies.....	43
3.1 Introduction.....	43
3.2 United Kingdom.....	44
3.2.1 Cotswolds.....	44
3.2.2 Cornwall.....	51
3.2.3 Ffestiniog Railway North Wales.....	58
3.3 The Cévennes, France.....	65
3.4 Construction Theories.....	70
3.5 Conclusion.....	71
Chapter 4: Council Study.....	74
4.1 Introduction.....	74
4.2 Assessment Methods.....	74
4.2.1 Gloucester Reports.....	75
4.2.2 Cornwall Reports.....	76
4.3 Conclusions.....	77

Chapter 5: Initial Study on Friction	79
5.1 Introduction	79
5.2 Literature Review	80
5.3 Laboratory Study	83
5.3.1 Laboratory Results	86
5.4 Field Study	90
5.4.1 Field Study Results	93
5.5 Discussion	94
5.6 Conclusions	96
Chapter 6: Geophysical Investigation	98
6.1 Introduction	98
6.2 Literature Review	99
6.2.1 Non Destructive assessment of Masonry	103
6.2.2 Ground Penetrating Radar (GPR)	105
6.2.3 Geophysical Technique Summary	106
6.3 The Study	107
6.3.1 Results	108
6.4 Conclusions	114
Chapter 7: Thermal Imaging	115
7.1 Introduction	115
7.2 Literature Review	117
7.2.1 Previous Structural Studies	119
7.2.2 Conclusions	119
7.3 Field Study	120
7.3.1 Northleach	120
7.3.2 Cévennes, France	133
7.3.3 Ffestiniog Railway, North Wales	141
7.3.4 Conclusions	145
7.4 Thermal Modelling	146
7.4.1 Results	149
7.4.2 Comparison to Northleach	160
7.5 Conclusions	171
Chapter 8: Discussion	174
8.1 Walling Styles and Assessment	174
8.2 Future Work	179
Chapter 9: Conclusions	182
9.1 Conclusion	182
References	186
Appendices	192
Appendix 1 – Walling Studies, Additional Images	
Appendix 2 – Council Study, Example Reports	
Appendix 3 – Initial Study on Friction, Additional Information	
Appendix 4 – Geophysics, GPR Images	
Appendix 5 – Thermal Imaging, Additional Images and WUFI Data	

List of Figures

Figure 1.1: Typical Drystone Construction Styles: Horizontal, Vertical and Random	12
Figure 1.2: Typical UK Walling Features	13
Figure 1.3 Lapped Through Stones	13
Figure 1.4: Running Joint Through Wall	14
Figure 1.5: Retaining Wall Constructions a) Double skinned; b) Single skinned	15
Figure 1.6: Typical Section through French style Wall	15
Figure 2.1: Burgoyne's Test Walls (a) Plan; (b) Sections (c) Schematics	21
Figure 2.2: Harkness et al (2000) Analysis Summary	23
Figure 2.3: Example of DEM model visual output and displacement graphs produced by Powrie et al. (2002) for varying joint stiffness	24
Figure 2.4: Burgoyne Wall D, velocity vectors (Claxton et al, 2005)	25
Figure 2.5: Comparison of deformation behaviour simulated using finite Element analyses (VISAGETM) and discrete element analyses (UDEC)	26
Figure 2.6: Wall Geometries Tested by Villemus with hydrostatic load applied to left side	27
Figure 2.7: Wall face displacement at varying eccentricities (k) relating to wall loading (left) and horizontal displacement (u) Vs stone position (y ₂) with dilated scale. Both for Wall 5, similar characteristics also shown by other walls	28
Figure 2.8: Images of wall 5 showing profile before loading (right) and after loading (centre and right) showing typical deformed shape	28
Figure 2.9: Colas experimental set up showing an engineered wall prior to testing (a) and following failure by overturning (b)	30
Figure 2.10: Mundell's Full Scale Experimental set up	32
Figure 2.11: Mundell's test wall 3 (a) prior to failure showing classic bulge shape, (b) bursting failure	33
Figure 2.12: Bulging failures on a ridged base as proposed by Cooper (1986) Showing thrust lines and deflected shapes; (a) idealised wall, (b) compressible wall	37
Figure 12.13: Wall cross section analysed by McCombie et al (2012) and Produced thrust lines and deformations under static loading	40
Figure 3.1: Cotswold wall locations	45
Figure 3.2: Garden retaining wall, Sherston	46
Figure 3.2a: Wall tie to corner of wall shown	46
Figure 3.3: Garden wall, Sherston	47
Figure 3.4: Vertical construction, Brompton Regis	48
Figure 3.5: Wall section, Northleach	49
Figure 3.6: New wall under construction	50
Figure 3.7: Map of Cornwall	52
Figure 3.8: Harbour wall, Boscastle, Cornwall	53

Figure 3.9: Herringbone wall in Boscastle, Cornwall.....	53
Figure 3.10: Vertical slate construction, Boscastle, Cornwall.....	54
Figure 3.11: Construction through wall, Boscastle, Cornwall.....	54
Figure 3.12: Open random construction, Mousehole, Cornwall.....	55
Figure 3.13: Mortared wall face, Mousehole, Cornwall.....	56
Figure 3.14: Mortared wall, Port Gavern, Cornwall.....	57
Figure 3.15: Mortared Wall, Port Quinn, Cornwall.....	58
Figure 3.16: Buttress example, Ffestiniog Railway.....	59
Figure 3.17: Foundation Protection, Ffestiniog Railway.....	60
Figure 3.18: Supporting wall on A497, Ffestiniog Railway.....	61
Figure 3.19: Cei Mawr, Ffestiniog Railway.....	62
Figure 3.20: Unstable wall, Ffestiniog Railway.....	63
Figure 3.21: Unstable wall realign, Ffestiniog Railway.....	64
Figure 3.22: Map of wall locations in France.....	66
Figure 3.23: River wall St Enimie, France.....	67
Figure 3.24: Historic wall supporting D998, France.....	68
Figure 3.25: Training wall, walling school, France.....	69
Figure 5.1: Zhang (2005) Roughness Scale.....	81
Figure 5.2: Stone Interlocking (Walker and Dickens, 1995).....	82
Figure 5.3: Initial tilt testing a) general set up, b) during testing.....	84
Figure 5.4: Final Shear Test Experimental setup.....	85
Figure 5.5: Stone friction angle and gradient of stone movement measured During shear testing of Quarry Limestone at an initial normal loading of 2.36 kN.....	88
Figure 5.6: Surfaces of Limestone tested in shear under an Optical Microscope.....	89
Figure 5.7: General arrangement at wall face showing 1m ² sample area marked out.....	91
Figure 5.8: Using a compass clinometer to record stone angles in wall.....	92
Figure 5.9: Hemispherical Projection Showing Normal Stone angles within the Wall at Northleach.....	93
Figure 5.10: Weathering of Limestone Contacts, Northleach.....	94
Figure 6.1: Using the GPR antenna to take readings of the wall.....	108
Figure 6.2: Areas of interest shown up using GPR.....	110
Figure 6.3: Scans along top and bottom of wall.....	111
Figure 6.4: Fill Excavated in area of interest to right of wall.....	112
Figure 6.5: Significantly large stone within wall corresponding to feature to left of GPR images.....	113
Figure 7.1: Northleach Wall Sections.....	121
Figure 7.2: Northleach Wall section 1.....	122
Figure 7.3: Example of geogrid tie being installed into wall section 1.....	122
Figure 7.4: Northleach Wall section 2.....	123
Figure 7.5: Northleach Wall section 3.....	123
Figure 7.6: Northleach Wall section 4.....	124
Figure 7.7: Northleach Wall section 5.....	124
Figure 7.8: Northleach Wall section 6.....	125
Figure 7.9: Northleach Wall Section 1 – Image taken 06/06/2013 at 20:00hrs.....	126
Figure 7.10: Wall Section 1 – Temperature comparison between through stones and general wall construction.....	127
Figure 7.11 Northleach Wall Section 1 –taken at 08:00 07.06.15.....	129
Figure 7.12: Northleach Wall Section 5/6. Image taken 06.06.2013 at 17:30.....	130
Figure 7.13: Northleach Wall Section 3. Image taken 06/06/2013 at 20:00.....	131

Figure 7.14: 3m High, North Facing Wall in L’Espinass on the D35, France.....	134
Figure 7.15: 3m High, South West facing teaching wall in Le Pont-de-Monvert, France.....	136
Figure 7.16: Le Pont-de-Monvert teaching wall under construction.....	138
Figure 7.17: 1.9m high, south facing wall in L’Espinass on the D35.....	139
Figure 7.18: Cei Mawr, North facing side of railway embankment.....	142
Figure 7.19: Between Tanybwllch and Ddualt, South-South East facing.....	143
Figure 7.20: Stone arrangements modelled using WUFI.....	147
Figure 7.21: Effects of orientation on temperature difference between Case 1 (Typical through stone) and Case 3 with 20mm air gaps (Typical UK wall construction).....	151
Figure 7.22: Average hourly temperatures over 1 year for each construction type.....	153
Figure 7.23: Style temperature Comparison over 1 year.....	156
Figure 7.24: Temperature Plot for August.....	157
Figure 7.25: Temperature Plot for December.....	158
Figure 7.26: Temperature Plot for April.....	159
Figure 7.27: Northleach Thermal Image and Simulation Comparison: 15:00 6.07.2013.....	161
Figure 7.28: Northleach Thermal Image and Simulation Comparison: 17:30 6.07.2013.....	162
Figure 7.29: Northleach Thermal Image and Simulation Comparison: 20:00 6.07.2013.....	163
Figure 7.30: Northleach Thermal Image and Simulation Comparison: 22:00 6.07.2013.....	164
Figure 7.31: Northleach thermal Image and Simulation Comparison: 05:30 7.07.2013.....	165
Figure 7.32: Northleach Thermal Image and Simulation Comparison: 08:00 7.07.2013.....	166
Figure 7.33: Northleach Thermal Image and Simulation Comparison: 10:30 7.07.2013.....	167
Figure 7.34: Northleach Thermal Image and Simulation Comparison: 13:00 7.07.2013.....	168
Figure 7.35: Temperature Comparison between Through type construction And General Construction for Thermal Simulations vs Thermal Images.....	169

List of Tables

Table 2.1: Angle of failure as recorded by Villemus (2007).....	29
Table 2.2: Mundell's Wall Loading, Data from Mundell (2009).....	33
Table 2.3: Risk categories as described by O'Reilly and Perry (2009).....	41
Table 5.1: Shear Testing of samples of Quarry Limestone, Weathered Limestone and Morte Slate under normal loads between 1 kN and 5 kN.....	85
Table 5.2: Measured Friction Angles during sliding and failure of Limestone and Morte Slate during tilt testing.....	86
Table 5.3: Mean Friction Values Across all Shear Tests Carried Out.....	90
Table 5.4: Locations of the wall study sites.....	90
Table 7.1: Typical Emissivity values.....	118
Table 7.2: Specific Heat Capacities of typical wall construction materials.....	118

Chapter 1

Introduction

1.1 Introduction

Drystone walling has been a part of the historic landscape for many years both in the UK as well as across many parts of the world, both in building structures such as the brochs found in Scotland and as walls, both field and retaining, which are common features across rural landscapes. Recently with a greater interest in sustainability and preserving traditional customs, drystone in general and retaining drystone walls in particular, have been the subject of an increased number of studies, described later in Chapter 2, looking into how they behave under loading, and how they withstand the imposed loads.

These studies encourage the use of drystone within new construction over more favoured modern constructions by increasing the understanding of the loads they are able to withstand under certain conditions, as well as providing clues as to how existing walls of a similar style will behave. However, there is little in the way of practical advice regarding how to assess these walls. A study in 1987 (O'Reilly et al. 2009) estimated that there were approximately 9000 km of retaining structures on the UK highways network, of which approximately 50% was estimated to be drystone, and that Network rail own approximately 19,000km of retaining structures many of which were considered likely to be of drystone, particularly in upland areas. There are also known to be a number of drystone features used in and around the coast and waterways of the UK, although figures for these are not available. While this number is likely to have decreased over

time through wall loss and replacement, this is still a significant number of walls under the care of public bodies which have a responsibility to assess these structures.

By understanding how these walls are constructed the assessor is better able to know which features need to be looked out for within the wall, and if these assist the wall or could potentially be detrimental to its stability. Much of the UK walling practice is derived from the free standing field boundary walls constructed as part of field clearance; principles of construction of the stone hedges or banks particularly found in parts of Cornwall and Wales, but also elsewhere, also have an influence on retaining wall construction. Information on the construction of these structures is widely available in publications from the Dry Stone Walling Association (DSWA 1999, 2008), however the basic and most important principles are outlined below.

1.2 Walling Construction

There are loosely three main types of common construction: Horizontal, Vertical, and Random as shown in Figure 1.1. Cross over between these styles can also be found as well as herringbone construction, though this is found less in retaining walls so is not considered in this work. Probably the most common form of construction is the horizontal style, around which most of the UK guidance is concentrated.

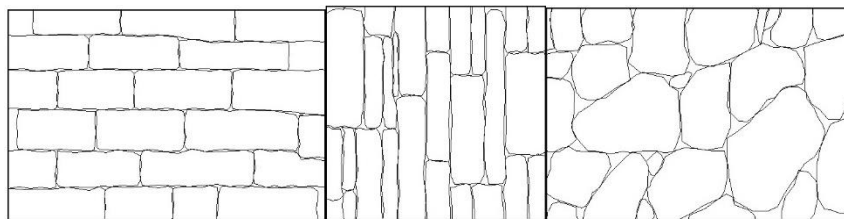


Figure 1.1: Typical Drystone Construction Styles: Horizontal, Vertical and Random

A typical UK horizontally constructed drystone wall consists of two outer faces with a well packed rubble fill as shown in Figure 1.2. The importance of the well packed fill is to aid transfer of the loads through the wall, so that it acts as monolithic as possible. If this fill were not there the back and front faces would act independently of each other in terms of resisting mass, and their resistance to overturning in particular would be greatly reduced.

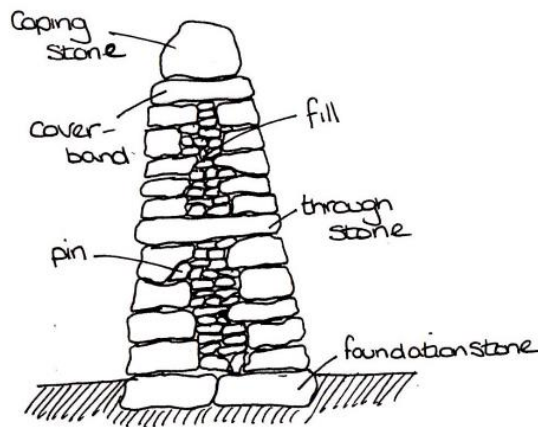


Figure 1.2: Typical UK Walling Features

Also tying together these faces together are through stones; these are large stones which span between the front and back face of the wall and can also penetrate into the backfill. These through stones prevent separation of the front and back faces, as well as helping to tie the wall to the backfill. DSWA guidance recommends that these are placed at approximately 600mm intervals throughout the height of the wall, though this may vary according to stone availability in different regions. Where it is not possible to find a stone large enough to span through the wall two smaller stones may be used and lapped into the centre of the wall as per Figure 1.3. For this a good contact needs to be ensured between the stones to enable loads to be sufficiently transferred. Good practice also dictates that stones should be used with their long sides into the wall. To make the stones in the wall more stable pinnings (small pieces of stone) may be used under the stones, to ensure they do not rock within the wall. These pinnings should be of as good a quality of stone as the face stone.

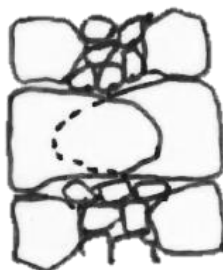


Figure 1.3 Lapped Through Stones

On the top of the wall cope stones are often found if stone availability allows. These help to tie the top of the two skins as well as adding weight to the wall; however these are often the first thing to be vandalised, so many historic walls, particularly if they are not well maintained, are often missing this feature. In some cases this has been replaced with a mortar cap. This carries out a similar job to the copes, as well as making it harder for stone to be removed over time.

A well-constructed wall will also have a batter or sloped back face that leans in towards the backfill. However some walls can be built vertically and over time due to movements this batter may not be as prominent. The stones within the wall should also be placed so that the vertical joints are crossed, and do not form a continuous vertical joint or running joint within the wall such as in Figure 1.4. By ensuring that the joints are crossed the wall is able to transfer loads along its face which reduces the risks of failure.



Figure 1.4: Running Joint Through Wall

Retaining walls may also be built with a single front face with larger stones behind which merges into the backfill as shown in Figure 1.5(b), in contrast with the more common double skinned construction shown in Figure 1.5(a). In these walls the good practices above should still be implemented, however from the front face the exact method of construction is not obvious.

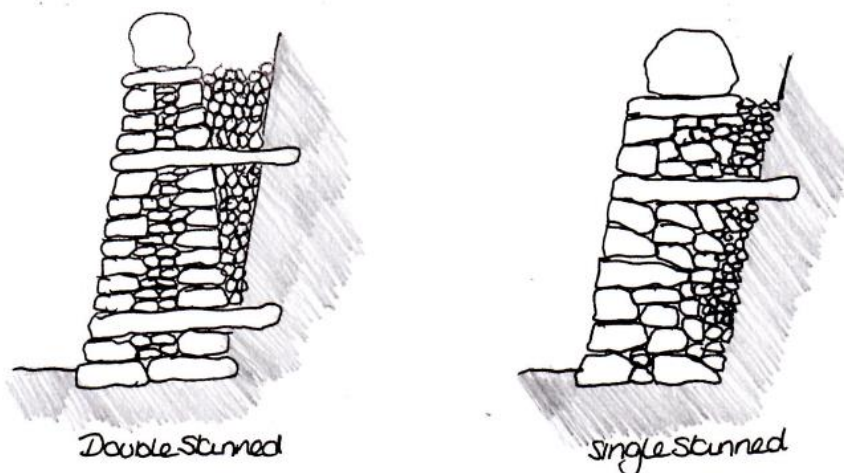


Figure 1.5: Retaining Wall Constructions a) Double skinned; b) Single skinned

In other parts of the world, such as France, horizontal construction tends to be have some significant differences. Advice on French construction can be found in CAPEB et al (2008). In France, particularly in the south, walling has grown around retaining structures, as opposed to free standing ones found in the UK. Walls in this region omit the two faced construction in favour of a more continuous construction using larger stones; these lap throughout the wall and mitigate the need for a rubble fill. Through stones also are not necessarily consciously built in here either, as the rear and front faces of the wall are already connected in well-constructed walls by the continuous lapping of the stones. However good practice still dictates the long edges of the stones penetrate into the wall and as such some stones become through like in nature. Here good practice still also dictates that joints should be crossed as in the UK, the internal joints of the structure should also be lapped to provide a continuous structure as shown in Figure 1.6.

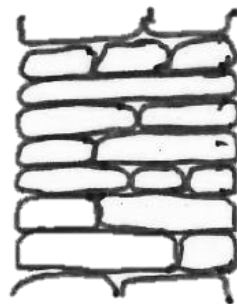


Figure 1.6: Typical Section through French style Wall

Vertical construction is constructed in a similar way to that of the French walls with the stones overlapped throughout the wall to create a more continuous structure. In vertical construction it is important that the stones are wedged with key stones at regular intervals, in a similar manner to that used in stone banks as described by Sean Adcock (1996). This ensures the stones are tight in the wall. The stones should also be placed upright so as to gain the greatest contact with their neighbouring stones. As with horizontal construction the stones should be orientated such that longest side is placed into the wall. It would also be advisable in larger retaining structures to avoid running joints along the length of the wall, though for stone banks the recommended form of construction is in rows of stone.

There is no real advice on random construction; however where possible the principles of good practice for the other construction styles would be followed to ensure the wall acts as monolithically as possible.

1.3 Aims and Objectives of Study

Many of the current walling studies (see Chapter 2) are based on full scale testing of structures, and ways of trying to mathematically assess the behaviour of these structures. This is because they are believed to behave unlike any other form of retaining wall due to their ductility and lack of bonded joints (O'Reilly P. et al 2009). While this is useful for the continued use of these walls as part of modern day construction, where the need to be able to explain things mathematically and be able to predict behaviours is key to getting these structures accepted by managing authorities. The fact that much of the existing stock has continued to function well over a hundred years does not provide satisfactory assurance of safety into the future, and for design loading conditions. Very few, if any, records are kept regarding the construction of these walls and hence even the basic details such as wall thickness are not known. Without these details, even a basic mathematical assessment cannot be carried out, even with these details due to the nature of these walls it is likely that if assessed by modern standards these walls would technically fail; we know they are not failing as they are still standing.

This first aim of this study is therefore to establish the relationship between theoretical approaches and the different construction methods found in practice. This will be achieved through discussion with wallers, and field studies, to provide an understanding of how these walls are constructed. This will entail investigation of how the builders intend the walls to resist the loads acting on them, and the influence of materials and their properties on the form of construction. Also through work in both France and the UK, it is hoped to gain an idea of the existing walling stock. In these areas walling styles, though similar, have some very distinct differences even with similar materials it aims to look at the reasoning behind this, and why this may have come about. In understanding the mechanisms and the variations that may occur and why, it can aid those assessing the wall when it varies from the text book construction and a view can be made as to why this may be. It also allows the assessor to use their engineering knowledge to decide if there are any features that may be detrimental to these when assessing the wall.

The second aim is then to establish through discussion with local councils responsible for these walls how they implement that responsibility. This requires gaining an overview off the different aspects of a wall that they look at, how they record them, and their practices in managing this assessment. This is necessary in order to gain an understanding of the ways in which any new insights could be exploited, and the types of tools which could realistically be used. A second benefit of pursuing this aim is to exploit the extensive local knowledge and records held by various authorities of the structures in their care. This leads on to a determination of the management and decision-making which follows on from an assessment. For example, would a distressed wall be replaced, repaired or monitored? If it is to be replaced, what factors might lead to replacement with another drystone structure rather than reinforced concrete?

The study then aims to investigate non-destructive assessment tools, to determine if there is a way in which these structures can be assessed reliably. From the good practice outlined in Section 1.2 it is known that there are potentially hidden features such as through stones within a wall that are likely to be critical to its stability; it is also known that other features are not beneficial, such as voiding inside or behind the wall, and water build up. Having identified potential methods, the most promising will be investigated in order to develop an understanding of how they can best be used to identify these hidden features.

By achieving these aims, it is intended that this work can be used to produce guidelines to improve the efficiency and reliability of the assessment of drystone retaining structures.

1.4 Thesis Layout

This thesis consists of nine chapters, and two appendices. The introduction is followed by the literature review which describes the major drystone studies carried out to date and their usefulness in assessing existing structures. This is followed by chapters with individual literature reviews as required, including the field studies carried and discussions with both wallers and interested parties. The thesis then moves onto the assessment of these structures. Preliminary work using GPR, which was not successful, is described, followed by a detailed practical and analytical investigation of the use of thermal imaging. These are then discussed and potential future work suggested to expand general walling knowledge, as the key to assessment of any structure is a sound knowledge of what it needs to work effectively.

Chapter 2

General Research on Drystone Retaining Walls

2.1 Introduction

Relatively few drystone walling studies have been carried out in comparison to other forms of retaining wall construction. Many of the current studies look at the behaviour of these walls and how this can be replicated mathematically, to ultimately aid in the design and assessment of these walls. Some of the most important work has been full-scale experiment, and analytical work has usually been in reference to this experimental work.

With the growing push towards sustainability many researchers in this field hope that with improved understanding, this traditional form of construction will become a viable option for new walls. Much of the current work carried out involves the use of full scale testing to look at the behaviours of walls constructed to match those local to where the research has been carried out. All full scale tests carried out to date have been on horizontally constructed walls.

The majority of these studies have been carried within the last 15 years mainly in southern France with one notable full scale testing study carried out in Bath, UK. Along with these some more historic works exist looking into drystone behaviour.

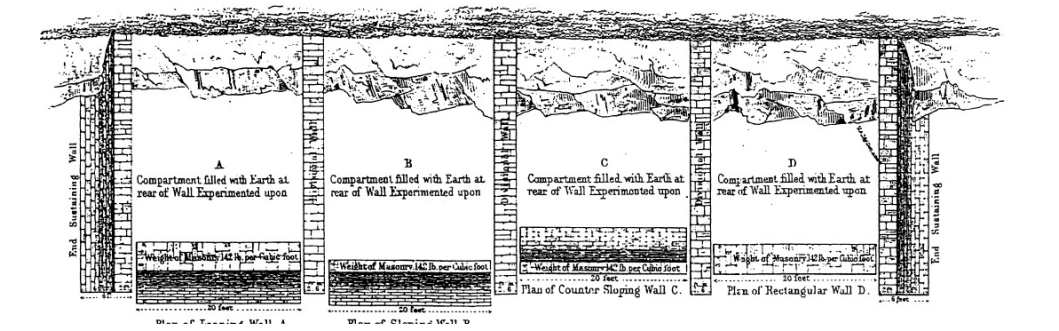
The studies previously carried out and how these help with the assessment of these structures is discussed below.

2.2 Full Scale Testing - Burgoyne

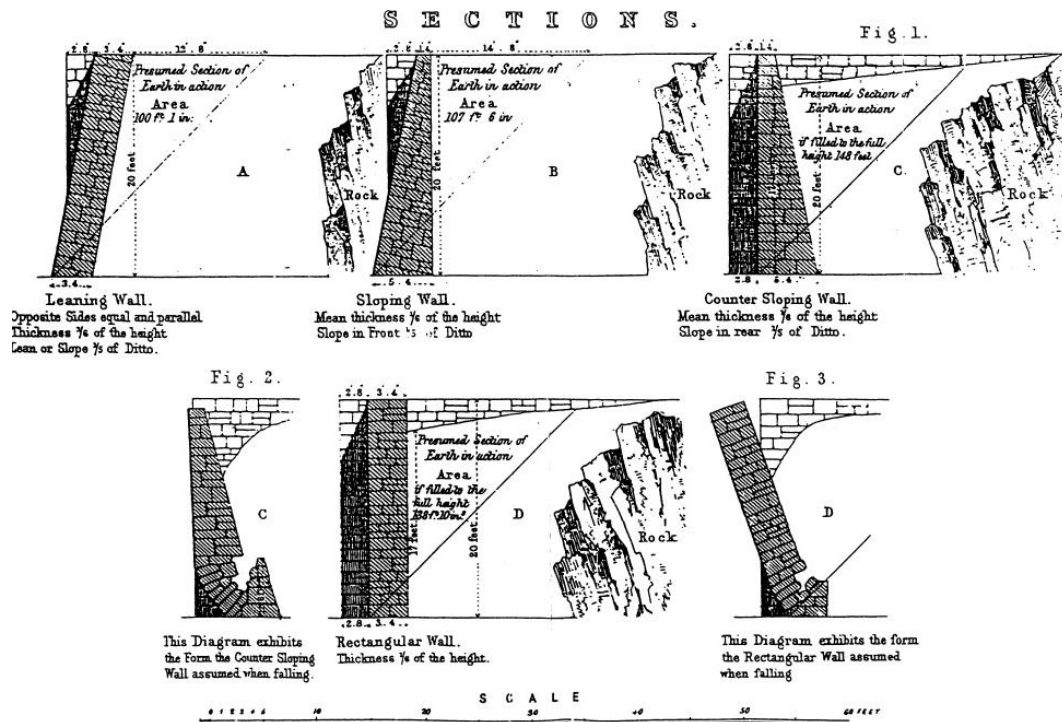
A number of full scale tests have been carried out over the last 15 years each looking at different aspects of failure. However, the predecessor to all drystone work was carried out by Burgoyne (1853) in Ireland in 1834.

Burgoyne's work forms the basis of much of the current walling work and was designed to investigate how wall shape and stone angle within the wall affects stability. In total Burgoyne carried out 4 experiments with each wall being constructed of squared granite blocks and 6.1m wide, and 6.1m high. Each wall was constructed to a different cross section, all with the same average thickness of around 1m, as shown in Figure 2.1, with the stones placed perpendicular to the wall face. Walls A and B had the stones sloping back towards the backfill and walls C and D had the stones level. Each wall was then backfilled to its full height or until failure occurred.

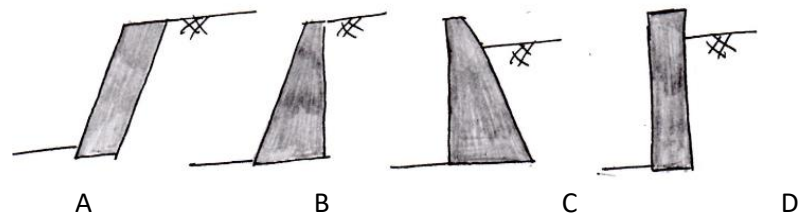
It was found that walls A and B were the most successful, maintaining stability to the full height, with wall B showing 64mm movement at its cope (approx. 1% movement). Walls C and D both failed with a backfill height of around 5.2m, showing different failure mechanisms. Wall C was recorded as showing bursting failure with the top section of wall falling vertically, Wall D was recorded as overturning. This study backs up general walling advice that stone should slope back into the wall. Through conversations with wallers, retaining walls are often constructed in a similar fashion to that seen in walls A and B, though some walls are seen constructed as in D, but not at the size seen in this experiment. The majority of the walling stock seen does not exceed 4-5m in height. Also the aspect ratio of the length to height is generally greater than 1 allowing loads to be redistributed though the wall; if the walls tested by Burgoyne had been longer they may have produced a greater load capacity.



a) Test Wall Plan



b) Test Wall Sections Including Failures



c) Schematic Diagram

Figure 2.1: Burgoyne's Test Walls (a) Plan; (b) Section; (c) Schematics (Burgoyne, 1853)

2.3 Summary of analytical work based on Burgoyne

No further full-scale testing was carried out until that by Villemus (see below) at the start of the twenty-first century. As a consequence, most analytical modelling work referred to the Burgoyne experiments.

Harkness et al. (2000) were one of the first to investigate analytical modelling of Burgoyne's walls and uses the discrete element program UDEC to model the full scale field trials carried out by Burgoyne. The results are also compared to limit equilibrium calculations. Harkness et al. modelled the walls using varying material parameters. Where Burgoyne has specified material parameters these have been modelled along with other realistic values of these. Where Burgoyne did not record parameters a realistic range of these values has been assumed and modelled in combination. The parameter that Harkness et al. required most thought on was the surface stiffness, and they conceded that until the advent of finite element analysis this parameter was not widely required. As such there is limited data and research into this to draw from. Hence a relatively low stiffness was taken as Burgoyne described his blocks as rough and the normal effective stresses are small.

By measuring the wall displacements and virtual failure heights Harkness et al. found that by using reasonable material properties good correlation to the field trials carried out by Burgoyne was seen. This provides a good basis for further use of DEM in investigating stability analysis of drystone walls. Figure 2.2 shows a summary of Harkness et al. parameters and results.

However both the study by Harkness et al. and Powrie et al (2002), below, while giving insight in behaviour patterns have limited practical application for assessment of real walls. The parameters required for DEM, both geometric and material, are unlikely to be known for any given wall and although reasonable assumptions may be made in part using other sources based on typical material properties, absolute certainty is unlikely to be obtained without some form of destructive investigations. This would somewhat negate the purpose of assessment. Harkness et al. also report modelling took a significant time with each run taking 7 days to complete.

Series 1 (Wall: density = 2650 kg/m³, friction angle = 45°; Soil: friction angle = 25°)															
Soil filling height	Soil density: kg/m³			Soil density: kg/m³			Soil density: kg/m³			Soil density: kg/m³					
	1400	1550	1700	1400	1550	1700	1400	1550	1700	1400	1550	1700			
6.1 m (20 ft)	NF			NF											
5.49 m (18 ft)	NF			NF											
5.18 m (17 ft)	NF			NF											
4.88 m (16 ft)	NF			NF			F			F					
4.27 m (14 ft)	NF			NF			NF			NF					
Series 2 (Wall: density = 2270 kg/m³, friction angle = 45°; Soil: friction angle = 28°)															
	Soil density: kg/m³			Soil density: kg/m³			Soil density: kg/m³			Soil density: kg/m³					
	1550			1550			1550			1550					
6.1 m (20 ft)	NF (Δ = 0.013 m)			NF (Δ = 0.032 m)											
5.49 m (18 ft)	NF			NF											
5.18 m (17 ft)	NF			NF			F			F					
4.88 m (16 ft)	NF			NF			NF (Δ = 0.082 m)			NF (Δ = 0.036 m)					
4.27 m (14 ft)	NF			NF			NF			NF					

Δ = horizontal deflection at top of wall; F = failed; NF = not failed.

Δ = horizontal deflection at top of wall; F = failed; NF = not failed.

Figure 2.2 Harkness et al (2000) Analysis Summary

Powrie et al (2002) carried out modelling of these test walls using 3-D Distinct Element Modelling (DEM), builds on work carried out by Harkness et al (2000), which were shown to adequately replicate the behaviour recorded during Burgoyne's experiments. Using Burgoyne's walls A and B Powrie et al. investigate the effects of varying geometry: wall block corner rounding; extent of backfill – i.e. distance between back of wall and rock face; joint inclination, and material properties: friction angle of backfill; friction angle and stiffness of joints; compressibility of sub base, on wall stability. In each case the walls were backfilled incrementally typically in increments of 0.3m in a similar manner to Harkness until failure occurred. Where required smaller increments were used to determine the exact failure height of the backfill.

In order to determine the effects of the changing these criteria Powrie et al. recorded the displacement at the top of the wall, the failure height and the probable mode of failure or potential mode of failure that would occur. Figure 2.3 shows typical outputs and comparisons made by Powrie et al. From their modelling they show that changing properties of the wall construction or backfill has an effect on the wall stability and potential mode of failure, and if potential failure could be predicted by looking at top of wall displacements. In some cases small variations in the factor being changed was found to have a significant effect on the wall stability, this highlights the difficulties in mathematically assessing these walls even where it is possible to make reasonable assumptions regarding the material and geometric properties of a wall.

Claxton et al (2005) also carried out DEM of the Burgoyne walls, and carried out a parametric study using a limit equilibrium model which showed that the critical mechanism was probably a rotation of a block at the base of wall D, leading to collapse of the wall. Using a more simplified model than either Harkness et al. or Powrie et al. Claxton et al. were able to reduce the run time down from the 7 days quoted by Harkness to 60-80min while still producing adequate results, making it a far more potentially practical tool for assessment where answers are often required within a short time frame. Claxton et al. were also able to model the typical heave soil profile immediately behind the wall, which they note is often seen prior to failure of real walls, as show in Figure 2.4 modelling the failure of Burgoyne's wall D. This also shows the typical velocity vector diagram produced by Claxton et al.

However as with Harkness and Powrie's works the model still required a number of parameters to by input that may not be known about the structure. Claxton et al also point out that Burgoyne's walls are not typical of the retaining wall construction found within the UK, as they lacked the fill core. Also all of the DEM model examples shown failed to create the typical bulge shape often seen within these walls in practise and simple showed toppling failure. However this is reflective of Burgoyne experiments themselves where no bulge shape was recorded.

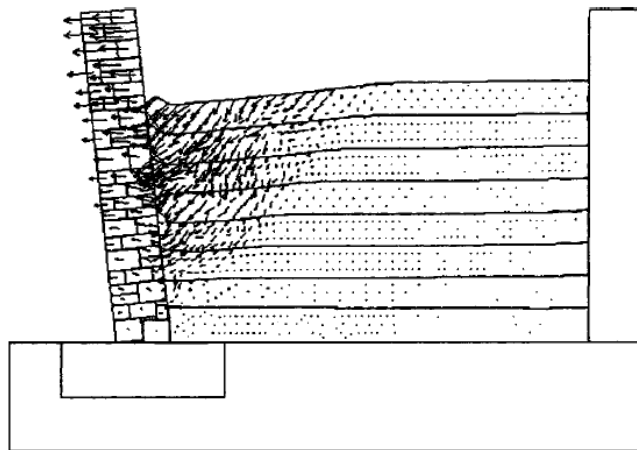


Figure 2.4 Burgoyne Wall D, velocity vectors (Claxton et al, 2005)

Zhang et al (2004) carried out modelling of these walls using Finite Element Analysis (FEA). They modelled the wall in two different ways, one modelling the wall as a continuum with lower overall properties to mimic the jointing of the blocks, and the other using joint elements to simulate the wall, defining the joint spacing, direction and stiffness. They found that similar results could be obtained using the finite element to that obtained using DEM by Harkness et al., with similar critical stable height of backfill obtained as seen in Figure 2.5. In comparison between the two finite element model types Zhang et al. found that the behaviour of the walls varied with the continuum model dominated by ductile deformation and showed a continuous smooth deflection increase until failure, while the jointed model was dominated by brittle deformation behaviour in a similar manner to the DEM modelling, with far less deformation than the continuum model, leading to a sudden failure. Through analysis of the stresses within the inner wall layer Zhang et al. also indicated a failure plane of 45deg to the wall base which replicated that shown in the field trials.

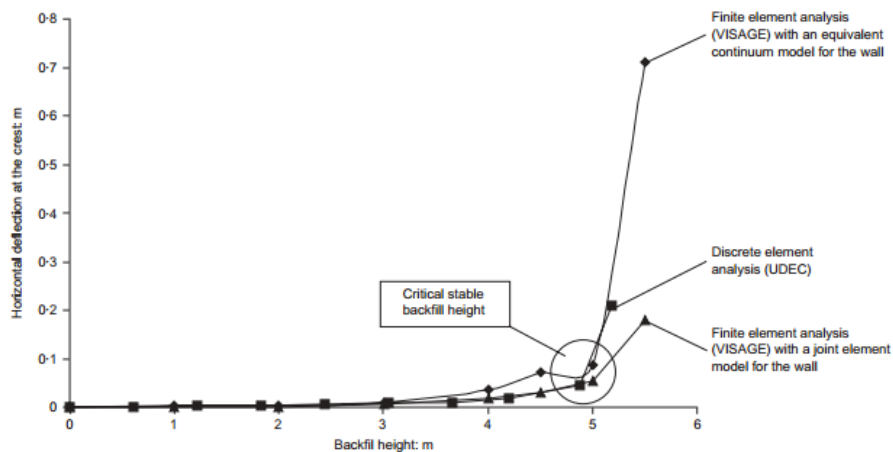


Fig. 2.5: Comparison of deformation behaviour simulated using finite element analyses (VISAGETM) and discrete element analyses (UDEC) (Zhang et al. 2004)

2.4 Experimental and analytical work by Villemus (2004)

Villemus' experiments, similar to those of Burgoyne, use a number of wall geometries, shown in Figure 2.6. They were reported in detail in his thesis (2004), and summarised in Villemus (2007). These geometries vary on both height and cross section, as well as differing stone inclinations with the same overall wall geometry. The majority of Villemus' walls were constructed using a local limestone with his final wall being constructed of local schist. However, unlike Burgoyne and Colas, Villemus chose to load his walls using hydrostatic pressure in the form of large water bags. These walls are also not tested to destruction, and failure is considered once the walls have deformed and bulged; once this deformation had occurred the water bags are removed to show the deformed profile, Figure 2.8. This was done to prevent friction on the back of the wall being mobilized, allowing forces to be more easily predicted, and to investigate the internal shear of the drystone masonry. In order to measure the wall displacement Villemus used photogrammetry of the wall ends and faces, recorded displacement for wall 5 are shown in Figure 2.7

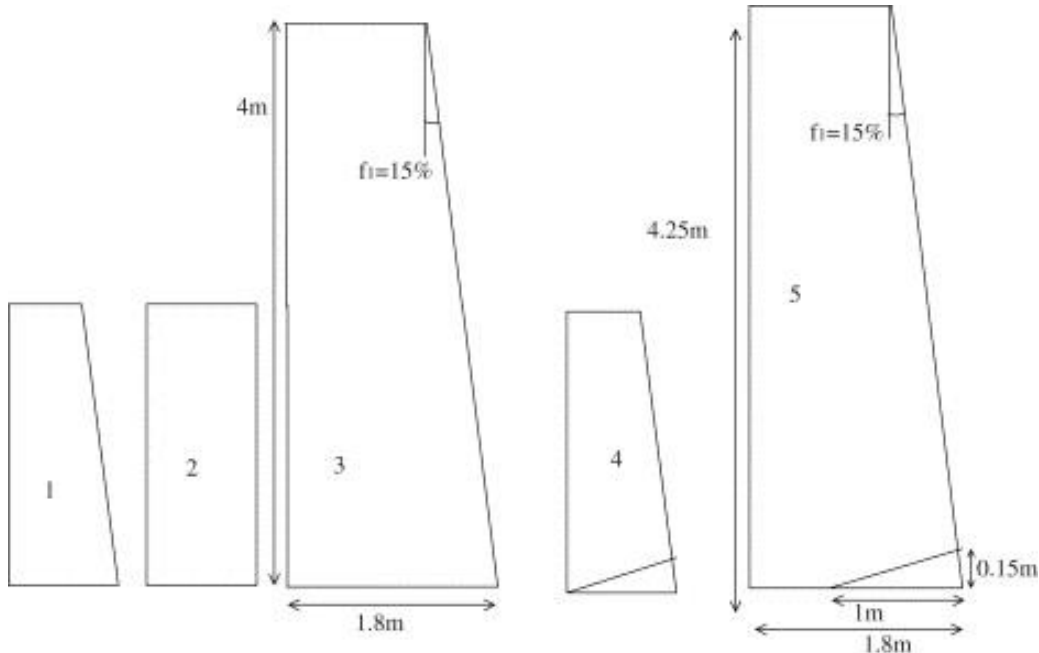


Figure 2.6: Wall Geometries Tested by Villemus with hydrostatic load applied to left side. (Villemus 2004)

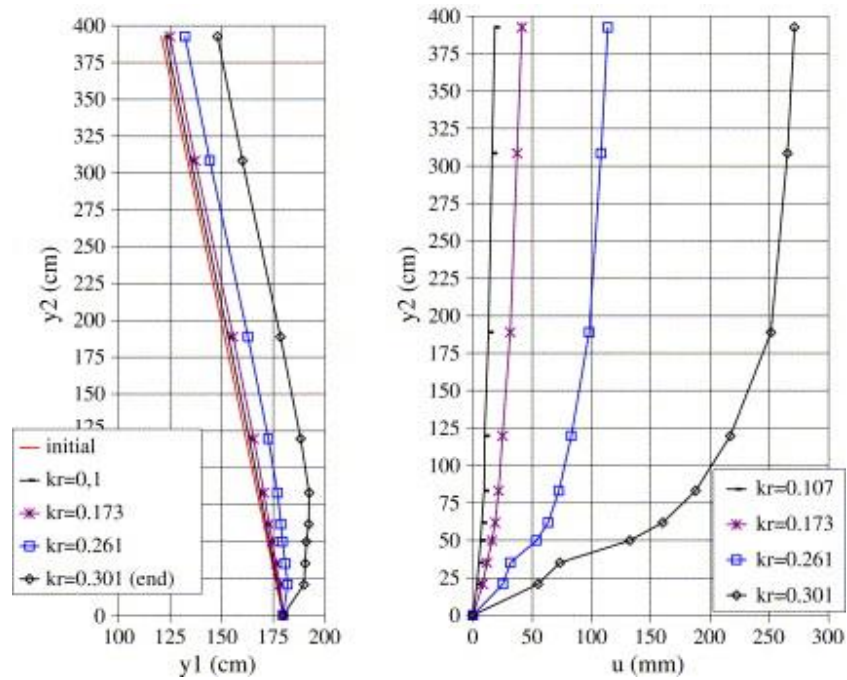


Figure 2.7: Wall face displacement at varying eccentricities (k) relating to wall loading (left) and horizontal displacement (u) Vs stone position (y_2) with dilated scale. Both for Wall 5, similar characteristics also shown by other walls. (Villemus 2004)



Figure 2.8: Images of wall 5 showing profile before loading (left) and after loading (centre and right) showing typical deformed shape. (Villemus 2004)

In conjunction with this, Villemus also conducted a number of shear box experiments on cut stones, arranged similarly to those within the wall. Shear box tests were carried out on both the limestone and the schist, with the schist only being tested under cut conditions. From the limestone however it appears that the in situ type test gave slightly increased frictional values to that of the cut stone.

This paper presents the findings of wall 5 in some detail, however no direct comparisons are made between the performances of the different walls constructed for this study. Which in terms of this current study is of more use. Actual and theoretical data is presented for each wall regarding the stone angles within the wall following deformation, Table 2.1, which allows the reader to gain some clues about the walls performance.

Table 2.1: Angle of failure as recorded by Villemus (2007)

	Value From	Wall 1	Wall 2	Wall 3	Wall 4	Wall 5
Failure Slope θ (degree)	Theoretical	11.3	9.4	10.5	1.5	-0.5
	Photogrammetry	N.M.	N.M.	11.5	3.5	0-2.5
Stone Rotation θ (degree)	Theoretical	11.3	9.4	10.5	5.5	8
	Photogrammetry	N.M.	N.M.	11.5	7.5	8.5-11

From comparison of the walls 3 and 5 which are of similar geometry with differing stone, it can be seen that the schist wall (wall 5) has a lower stone angle displacement than the limestone wall, implying less force is required for failure to occur, comparing walls 1 and 2 it can also be seen that the vertical faced wall has a smaller stone rotation, implying a smaller force would be required for failure. The anomaly in these results is wall 4 which is of similar geometry and size to wall 1 with the stone inclined into the wall face. This would imply wall construction 4 was less stable than wall 1. However without full displacement data for the wall face it is hard to fully conclude this. It may be that wall 4 deformed less than wall 1, hence the lower rotational values, or that differing mechanisms were involved. Overall Villemus' study could provide useful insight into the behaviour of varying geometries, however with the currently available texts this is not fully presented.

Villemus showed a limit equilibrium analysis could predict the initial yielding of the test structures.

2.5 Experimental and analytical work by Colas (2009)

In Colas' experiments the effects of construction style are considered on a wall's capacity. In these experiments two walls of similar geometry were constructed, one considered to be a well-engineered wall, the other considered to be of rural construction, which is often deemed to be of poorer construction. The main visual difference between the two is the finish of the wall face, with the engineered wall having a much neater and well packed face, in comparison to the rural wall. The engineered wall also took considerably longer to construct, taking 2 weeks compared to 2 days for the rural wall. These walls were then loaded as in Burgoyne's experiments by increasing the back fill height until failure occurred. Under loading it was found that the engineered wall actually failed before the rural wall with a back fill height of 2.41m high whilst the rural wall was backfilled above its height and then required additional vibrational forces to induce failure. Both walls failed in toppling as might be expected with this form of loading.



Figure 2.9: Colas experimental set up showing an engineered wall prior to testing (a) and following failure by overturning (b). (Colas 2009)

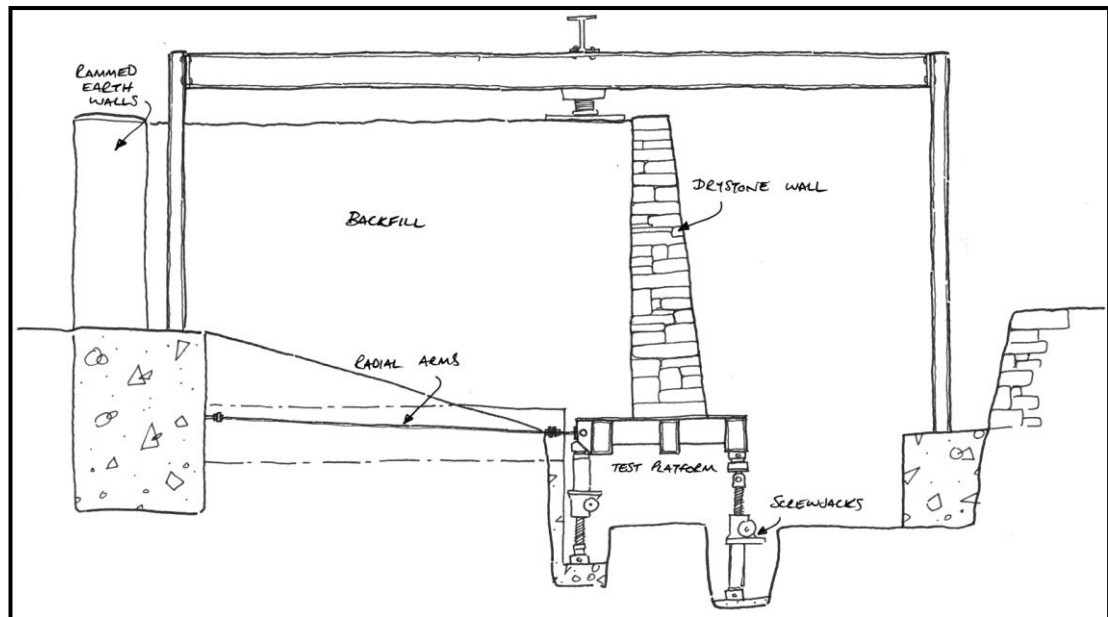
These experiments suggest that perceived quality of construction may not actually be a fair representation of the actual quality of the wall and that in order to fully assess a wall's strength, factors other than its face appearance need to be considered. There are some minor differences between the two walls that may have aided the rural walls

behaviour, it was slightly wider than the engineered wall at its cope and the joint inclination was higher, i.e. the stones sloped into the wall more, however this again are not features that would be immediately obvious at the wall face and if assessment were based on face quality alone then it is likely the rural wall would be deemed less stable.

2.6 Experimental work by Mundell (2009)

Mundell's study (2009) in comparison to Colas and Villemus, is the least comparable to Burgoyne's original study. Mundell's study was very specific to the walling style found in and around the Cotswold area of the UK and of all the full scale tests carried out, replicates what is found in the field, in terms of actual loading and mechanism between the wall and backfill. In addition, Mundell's work was the first to consider three dimensional aspects with walls long in plan and non-uniform loading along the wall length. Mundell's study consisted of a number of walls of varying construction quality and material which were then backfilled and displaced as a whole to mimic backfill settlements; additional surcharge was then applied over a small area (such as the area of a wheel) and loaded until complete failure occurred. At various points the load was also kept stable/removed to establish if the displacements seen were stable or of failure continued.

In total Mundell constructed 5 walls of varying construction quality including one wall constructed using Morte slate. The rest of the walls were constructed using limestones local to the area. Of the limestone walls, Wall 1 was of highest quality, many of the stones being worked, taking the most time to build and with a greater number of larger stones which penetrated deeper into the wall. Wall 2 was constructed similar to Wall 1, but purposely of a lesser quality with less working of the stones and fewer pins, showing visually as a lower build quality; this wall was also more slender than Wall 1. Wall 3 was constructed much more quickly using a greater number of smaller stones and fewer larger stones extending into the wall. The construction quality of this wall was such that individual stones could easily be moved within the face by hand. Wall 4 was constructed to be as similar to wall three as possible.



(a) General Experimental Set up



(b) Experimental Set up showing a typical wall prior to testing

Figure 2.10: Mundell's Full Scale Experimental set up (Mundell 2009)

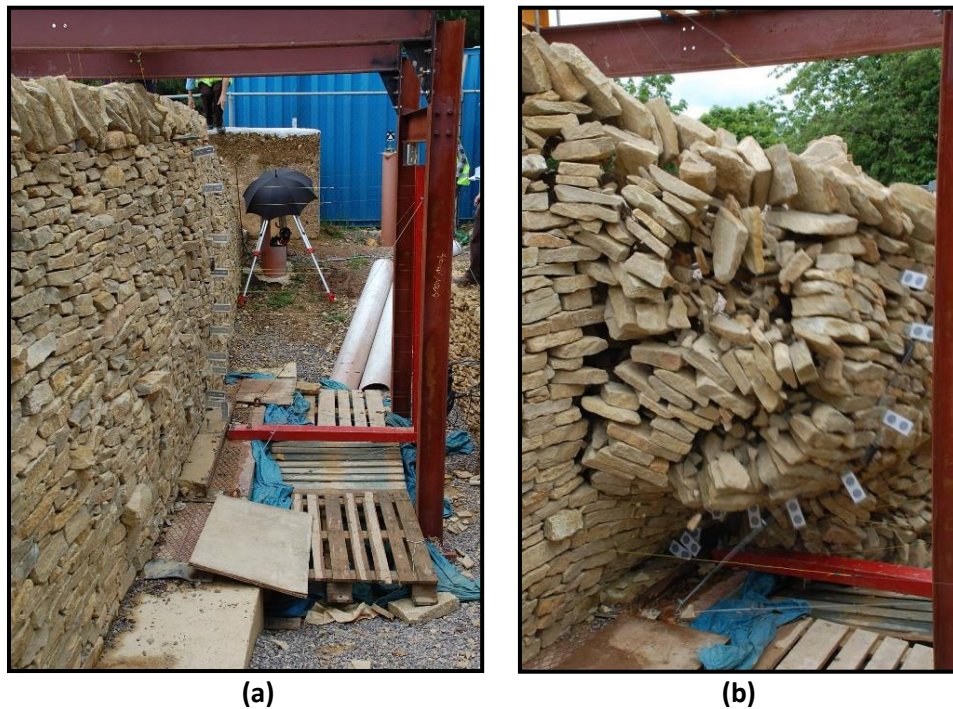


Figure 2.11: Mundell's test wall 3 (a) prior to failure showing classic bulge shape, (b) bursting failure. (Mundell 2009)

All of Mundell's walls were found to bulge prior to failure; however the failure mechanisms between the construction styles varied, along with the peak loads that could be applied as shown in table 2.2.

Table 2.2: Mundell's Wall Loading, Data from Mundell (2009)

Wall	Peak Load	Load prior to Failure	Failure Mechanism	Bulge distortion from vertical	Additional Comments
Wall 1	110kN	40kN	Toppling	425mm	Toe of wall dropped to mimic bearing failure under wall
Wall 2	75kN	47kN	Toppling	150mm	Movements at base suggest failure instigated by block rotation unlike in wall 1
Wall 3	75-80kN	45kN	Bursting	350mm	Local failure occurred prior to main failure
Wall 4	85kN	61kN	Bulging/Toppling	250mm	n/a
Wall 5 (Morte Slate)	60kN	24kN	Sliding/Overturning	300mm	Wall showed most movement during back filling and test set up of all 5 walls.

Mundell's experiments show that a high quality of construction does indeed provide the greatest resistance to applied loads (Wall 1). However, the less well constructed limestone walls were still found to have peak additional loads of around 68-77% that of Wall 1. These loads are also in the region of maximum imposed wheel loads for heavy good vehicles on medium traffic roads with a good surface, as outlined by BD21 (2001). The capacity will also be affected by other factors including the distance back from the top of the wall the load is applied, and the tyre patch size and load duration. This suggests that provided that road surfaces are well maintained in the majority of cases even where construction is not of the highest quality, these walls are able to withstand the applied loadings. However this is not the case for the Morte slate that showed considerably less resistance to the applied loading.

The main variations caused from the different constructions appeared to be the failure mode. Where stones are smaller and less blocky bulging and bursting appears to be the prevalent form of failure (Figure 2.11 (b)). The wall was also found to have smaller displacements prior to failure, perhaps unsurprising as this must be limited partially by the stone size itself. Where the walls were constructed with more stone penetrating into the wall toppling became the prevalent failure. This is supported by Colas' work where both her walls failed in toppling also. From knowledge gained regarding construction techniques in France it is likely that her walls were constructed with little to no fill and with a number of stones placed such that they also penetrated into the wall. Where stones penetrate into the wall it is less likely that they can rotate relative to each other, and so form the mechanisms required for bursting; therefore, failure occurs when the wall as a whole is unable to resist the forces applied. In contrast, smaller stones that do not penetrate the wall have a greater ability to rotate against each other and hence reach the point where contacts are no longer sufficient to maintain the frictional forces required within the wall and hence bursting occurs.

Mundell's experiments also start to explore the differences in failure mechanisms between different stone types and hence different frictional properties. With the lower friction Morte slate not only did failure occur more rapidly, but the wall showed a distinct planar of failure near its base on which sliding occurred until the wall had moved so far forward that it toppled off its base. Where walls are constructed using stones of a lower friction angle it is not uncommon to see them constructed using different

construction styles to those tested, which will certainly improve their ability to withstand loading as discussed in Chapter 3.

2.6.1 Overall Conclusions

The full scale studies that have been carried out provide a useful overview of how different constructions and construction qualities affect the load capabilities of drystone walls. In general it can be said that constructions that batter back into the retained materials are often more effective than those that don't; also where stones slope back into the wall, this assists the wall in resisting loading.

The studies also discovered that build quality (most easily distinguished/assumed from face appearance) is not as detrimental to wall capacity as may be expected; it can be that giving too much priority to the appearance of the face can result in a weaker wall.

However, by the nature of these studies the walls tested are all of a construction style that is local to the area of testing, so they are all horizontally constructed walls, built from a limited range of materials. It could therefore be argued that the tests only provide real insight into a limited number of construction that are similar to those tested.

Also, by the nature of the experiments all the walls tested were of new construction and using new materials. It is known that in the UK in particular much of the walling stock is around 100 yrs. old. Within this time it is likely that degradation will have occurred. For example, Cotswold wallers often report evidence of material loss when dismantling walls for rebuilding. Other factors may also have affected the walls, which would result in different behaviours from what was seen in the test walls. However it is unlikely that permission would be given to carry out in-situ testing on an existing wall that has stood for a significant period of time. Construction using materials from dismantled walls that are old enough for the stone to have degraded to an extent may be possible, and would replicate the rebuilding of walls which is not uncommon. This may help the development of an understanding of how older materials may affect the capacity of these walls.

These full scale tests also show that while collapse of these walls is as expected an instantaneous happening, the actual failure leading to collapse is not; if a wall is well

monitored then signs of failure, such as continued outward movement of the face, can be picked up some time before collapse occurs.

In terms of wall assessment these experiments help provide indicators that suggest how a wall may perform or react to certain situations, however for the reasons outlined above, they should be used with some caution when looking at historic walls. However, the testing carried out does provide strong arguments for replacing these older structures with new equivalent structures, as opposed to other modern favoured methods e.g. concrete. This would not only be more sustainable due to the methods used, but often will provide a better visual appearance and help to maintain traditional trades. The testing carried out have shown that these walls are more than able to withstand potential design loads.

Following on from these full scale tests, as well as though other studies, a number of models have also been proposed to mimic the behaviour of drystone. These are discussed below.

2.7 Drystone modelling

This study does not look at the walls mathematically, but aims to provide a qualitative overview of the mechanisms that enable these walls to withstand the forces on them. This study also aims to indicate practical methods to aid assessment; it is worth acknowledging the analytical models that have been proposed for the assessment of walls as these have the potential to become assessment tools in their own right.

Probably the most easily accessible of the mathematical approaches to looking at drystone is proposed by Cooper (1986). Cooper uses a number a number of simple equations to calculate the eccentricity of the resultant forces within the wall at each stone layer, to determine the line of thrust through the wall. Whether this line of thrust lies within the wall then determines if the wall is stable, and the position of the line of thrust within the wall indicates the failure mechanisms that are likely to occur. This method can easily be set up in a simple spreadsheet. Cooper also makes some allowance for stone weathering by altering the effective width, reducing the width where stones have become more rounded at their corners. However, the method treats the entire width of the wall acts as one block for any given depth. Where walls are well

constructed, with suitable through stones in the case of horizontal construction, or are built continuously, as can be found in France, this method is likely to provide a fair representation of the wall behaviour. However, where the wall is not constructed well and the back and front faces act independently, this is less likely to provide a fair representation of failure mechanisms. Also it is unclear if this is valid for other construction styles i.e. vertical and random constructions. It is possible that by increasing the depths of the elements within the wall some representation of vertical construction can be made. However, this method is less likely to be of use for random construction, particularly where the stones are more rounded and boulder like.

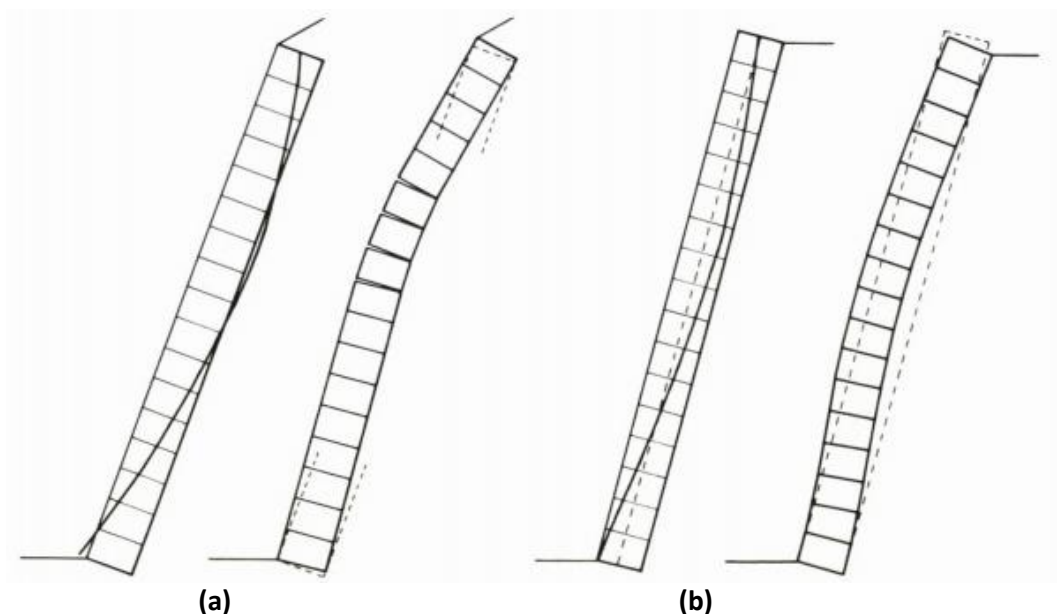


Figure 2.12: Bulging failures on a ridged base as proposed by Cooper (1986) showing thrust lines and deflected shapes; (a) idealised wall, (b) compressible wall.

Mundell (2009) expands on Cooper's theory to produce a limit equilibrium programme where wall data can be input, along with basic soil properties to produce the line of thrust within the wall and give an indication of failure mode, if failure is to occur. Mundell also allows for initial deformations within the wall as well as additional surcharge loadings behind the wall face. Like Cooper, Mundell also allows for rounding of corners of the stone mimicking weathering and allows the stone heights to be adjusted. Wall geometry data is compiled as a .csv file which can then be input into the program. Initial deformation can be input either within this file or once drawn within the program can be manually dragged by the user to desired shape.

However both of these methods require certain assumptions about the wall and backfill to be made. Some of these can be made fairly easily if basic stone or soil attributes are known, as there is widely published guidance as to friction angles and densities for a variety of soils and stone types. Fill height can also easily be determined by knowing the height of the wall and the height of any parapets if present. However both Cooper and Mundell require the wall thickness to be known. If the top of a wall is accessible it may be possible to determine the width here and using rules of thumb a base width could be approximated; however, to determine this accurately is near impossible, particularly where a wall may be unstable and it is deemed unwise to gain access to its crest. Mundell also requires percentage of voids by volume to be known, again in an existing wall this is hard to determine. Through voids testing Mundell found that in newly constructed samples void were between 21% for a well constructed wall to 37.5% for a poorly constructed wall. Where stones are not so prone to weathering taking a value within this region may be viable. In limestone areas where material loss is known to occur a higher value may be required, but it would be feasible to adjust this value to see where failure would occur and make a judgement on this. Mundell's program, like Cooper's theory, also has the potential to be adapted to deal with vertical construction, but both would need to be validated against full scale testing should any be carried out.

As well as the above a number of other models have been proposed by various authors using a number of differing modelling techniques. Harkness et al. (2000) use a discrete element code UDEC to model drystone behaviour, in particular to model and verify the experiments as carried out by Burgoyne, and they were able to replicate his results fairly well. These were then replicated by Powrie et al (2002) who was part of the initial group to look at Burgoyne's first two walls in greater depth. This technique was also initially used by Dickens and Walker (1996), to model walls being studied in Zimbabwe, where it was suspected that the wall failures here were caused by the settlement of the core materials. Once validated it was then used to investigate other factors that could affect stability.

During the study of the models to investigate Burgoyne's walls and the Zimbabwean walls a number of other factors were also looked at which could affect stability, such as void and stone size, the influence of through stones on bulging (Walker and Dickens, 1996), the effects of stone rounding, the effects of backfill and jointing in the wall (Powrie et al. 2002). While these investigations aid general wall understanding, in the

assessment of specific walls the methods still depend upon a number of key points being known about the wall with regard to geometry and internal structure, which is rarely known. In the case of Walker and Dickens, walls had already failed/partially failed so the internal make up of the wall could be investigated

Zhang et al. (2004) use finite element analysis to analyse wall structures, again using Burgoyne's experiments as a basis for their model, while Colas et al. use yield design to model the walls tested in Villemus's experiments (2007). Colas also expands on this work, presenting modelling of small scale dry joint masonry structures in 2010 (Colas et al, 2010). Walker et al (2006) also present a model using plane strain to model wall behaviour under loading. All of the above models allow the wall to be modelled in a more complex way to that seen in Cooper and Mundell's work, considering the structure through the wall as well as the individual layers. Again, while these may help with the assessment of walls where parameters are known it does little to help with the assessment of existing structures.

McCombie et al (2012) build on the work of both Mundell (2009) and Cooper (1986), by using the program of Mundell reported above to analyse all five experimental walls constructed by Mundell. Figure 2.13 shows the initial profile of each wall and the final profile found in the experiments. The analyses correctly indicated failure to just take place at the final profile for walls two to five. However, for wall one the two-dimensional nature of the model gave a conservative result, because the ability of the wall to transfer load along the face through tension in the face was ignored. This meant that the model indicated that the wall should be unable to stand at the final profile it achieved. McCombie et al. concluded that the model is a useful tool in the assessment and design of drystone retaining walls. The outputs from this approach are also more user friendly than that produced by the DEM models (as seen in Powrie et al and Harkness et al.). This modelling method also has a greatly reduced processing time, with thrust lines and deformations produced almost immediately. However, as with the other modelling methods seen, it still requires certain properties about the wall to be known or assumed, which produces its own inaccuracies within the model.

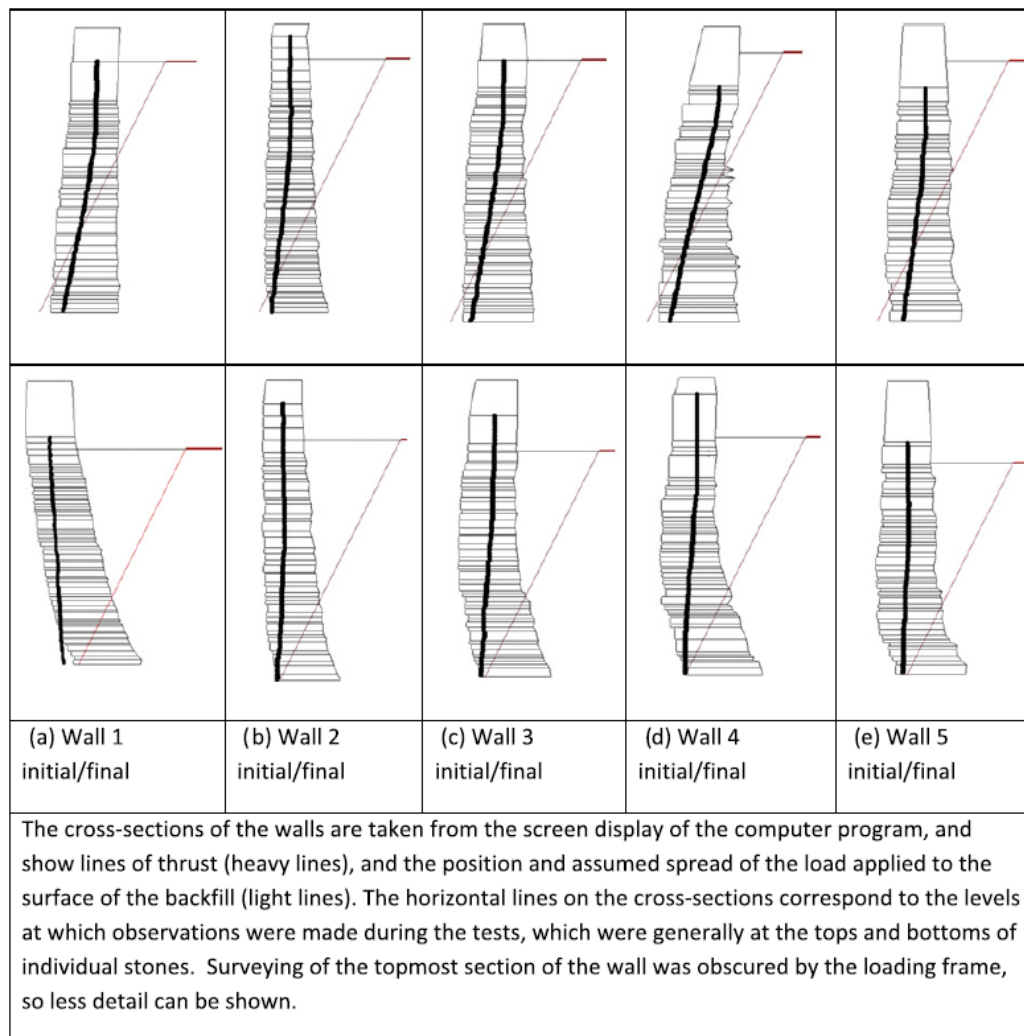


Figure 2.13: Wall cross section analysed by McCombie et al (2012) and produced thrust lines and deformations under static loading.

Overall modelling, while recognised as a useful tool in the acceptance of drystone, relies on a number of parameters being known prior to any assessment being made. Due to the lack of information known about these walls or their construction it is unlikely that satisfactory results can be obtained for existing walls currently in use. Also the running time of programmes may be an issue, for example it was reported that due to the complexity of the model some of Harkness et al. models took around 7 days to run, though this time would certainly be considerably reduced using modern computers. These models have also only been validated against horizontal and blocky constructions, so it is unclear if they would be valid for other construction styles. However even if information can be gained regarding the wall structure, and assuming they are suitable for all construction styles, the main limitation to their use is their availability. With the exception of Cooper's work which can be placed into a spreadsheet, the other models

proposed do not have a widespread availability. Mundell's program can be downloaded from a web page, but the other systems use expensive proprietary software.

2.8 Practical Walling Advice for Assessment

Practical assessment guidance is quite limited. The Drystone Walling Association have a number of good construction guides published, and there are also the French guidelines, the basics of which are outlined in Chapter 1. The other main guidance comes from CIRIA C676 by O'Reilly and Perry (2009), "Drystone retaining walls and their modifications - condition appraisal and remedial treatment".

O'Reilly and Perry provide a background to drystone retaining features within the UK, and highlight the main points they consider need to be looked for during assessment. They also include the specific recommended assessment criteria and procedures likely to be required by the main asset owners for canals, highways and railways. They then go on to describe useful ways of monitoring these walls over time. The report also provides guidance on the risk categories of the walls as shown below in table 2.3.

Table 2.3: Risk categories as described by O'Reilly and Perry (2009)

Category	Wall Height Inc Parapet	Location
A	Exceeding 3m	Walls above or supporting locations frequented by people such as transport infrastructure, habitations, footpaths, playgrounds, camp sites, caravans and car parks
B	3m or less	
C	Any height	Walls abutting agricultural land and not frequented by people.

Following on from this, guidance is also given for repair, this includes the use of mortar so long as appropriate weep holes are provided, soil nailing, thickening of the wall, buttressing, proving embankments, and rebuilding. When carried out correctly it is likely that these all help increase a wall's stability. However, it is often seen that the use of mortar does not include the provision of weep holes, this can lead to the build-up of water pressures behind the wall which is detrimental to the wall stability; it also reduces the flexibility of the wall, which is likely to be detrimental to how the wall transfers loading, and hence detrimental to its stability.

With regard to replacement a number of options are also put forward, predominantly these are concrete based with a stone facing to match the original, or fully mortared walls. Many researchers working in this field hope that the work carried out within other studies will lead to the replacement of these walls using drystone will become more prominent.

At the end of the document O'Reilly and Perry summarise research to the date of publishing, and provide extracts from relevant documents useful for assessment.

O'Reilly and Perry also concede that much of drystone assessment is based on engineering judgement, although under highway and rail guidelines drystone structures should be assessed in a similar way to more modern structures, including mathematical analysis. B

2.9 Conclusions

There have been a number of walling studies, the majority within the last 20 years. By their nature these have been influenced by construction practices in their locality, and all of which have been carried out on horizontal construction. There have also been a number of models proposed which have been validated against the full scale tests carried out. While these all aid the greater understanding of walling with regards to assessment of current structure, they may have limited practical usefulness due to a number of factors. Again by the nature of the full scale trials, all the walls tested have been new build, and have not been affected by 100 years or so of in situ weathering and loading. For the modelling a number of details are required regarding construction and backfill that are unlikely to be known without intrusive investigation, which partly defeats the objective of the assessment.

With regard to current assessment advice O'Reilly and Perry provide a comprehensive guide to walling assessment and repair, however the identification of features within a wall may be an issue as assessment has to be carried out at the wall face.

Chapter 3

Walling Studies

3.1 Introduction

The detailed form of construction of drystone retaining walls is critical to their stability and performance, yet previous studies have tended to assume that walls are tightly constructed with well-fitting rectangular blocks (e.g. Burgoyne 1853, Zhang 2004). In order to arrive at a better understanding of the range of behaviours that may be found in practice, studies were undertaken within the UK and France. The methods of study involved visual inspection, measurement, and discussion with wall builders.

The study considered three factors –

- Age
- Building styles – both overall as well as subtleties within styles
- Use

These studies also enabled the factors that may influence construction styles to be seen, as well as allowing ideas regarding their construction to be formed; hence, insights could be gained into the mechanisms that may be involved in their ability to resist the forces placed upon them via the backfill. These walling theories are discussed later in this chapter

Studies were carried out in the UK, in the Cotswolds, Cornwall and on the Ffestiniog railway, and in France in the Cevennes, where drystone retaining walls are prominent.

This area of France has also been subject to walling research and allowed comparisons to be made between the walling traditions of the UK and France.

3.2 United Kingdom

Within the UK, the three areas of interest studied were, the Cotswolds, which is well known for its regular construction style and pale stone; Cornwall, best known for its Cornish banks, but also having a diverse range of other drystone structures, including coastal features, and the Ffestiniog railway, which is unusual due to the massive scale of its drystone embankments. The studies of these areas are discussed below.

3.2.1 Cotswolds

The Cotswold area was chosen due to its proximity to Bath and is well known for its particular style of walling, with the style named after the area. The majority of the walling in this area is constructed using local limestones. These limestones can vary, depending on their source, from fine oolitic limestone, to more coarse shelly stones – these stones also give Cotswold walling its distinctive colour. The majority of the walls in this area are freestanding and define field and property boundaries. However, a significant number of retaining walls exist.

The majority of stone used in the Cotswolds is relatively small and flat with straight sides, giving a conventional wall appearance. Freestanding walls are constructed with two outer faces of larger carefully placed stones, and the space between tightly packed with rubble fill, as described in Section 1.2. Through stones play an important role in Cotswold walling, tying the two outer faces together and providing stability. In retaining walls, this form of construction can also be found, with the through stone potentially extending into the backfill to tie the wall in. The back face may be omitted in retaining walls, and instead it is graded into the backfill, still with the use of through stones to tie the structure into the backfill, see Figure 1.5.

The area is outlined below with details of some of the walls studied. Further walls from this area can be found in Appendix 3 where they are studied in more detail in Chapter 5.

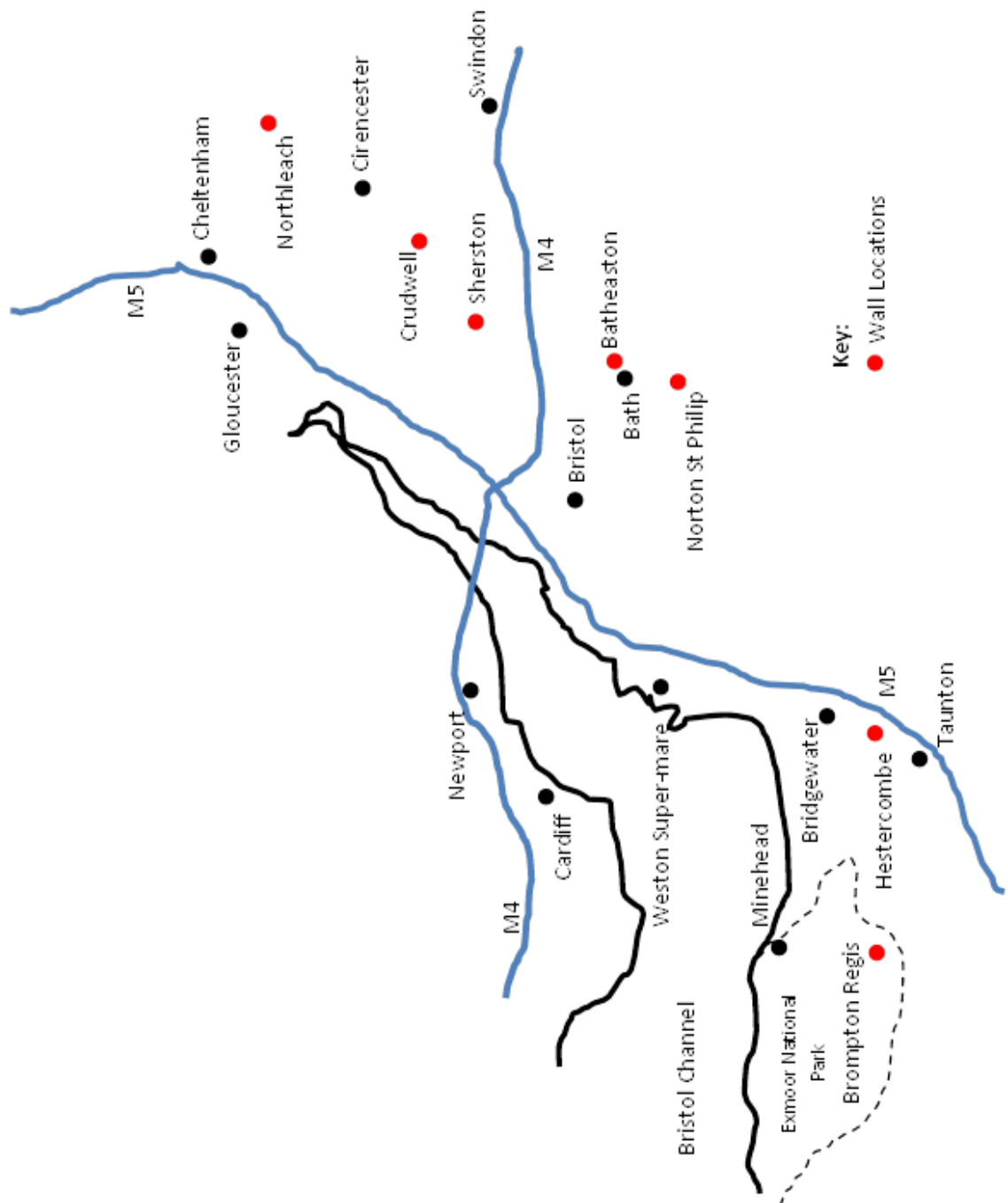


Figure 3.1: Cotswold wall locations

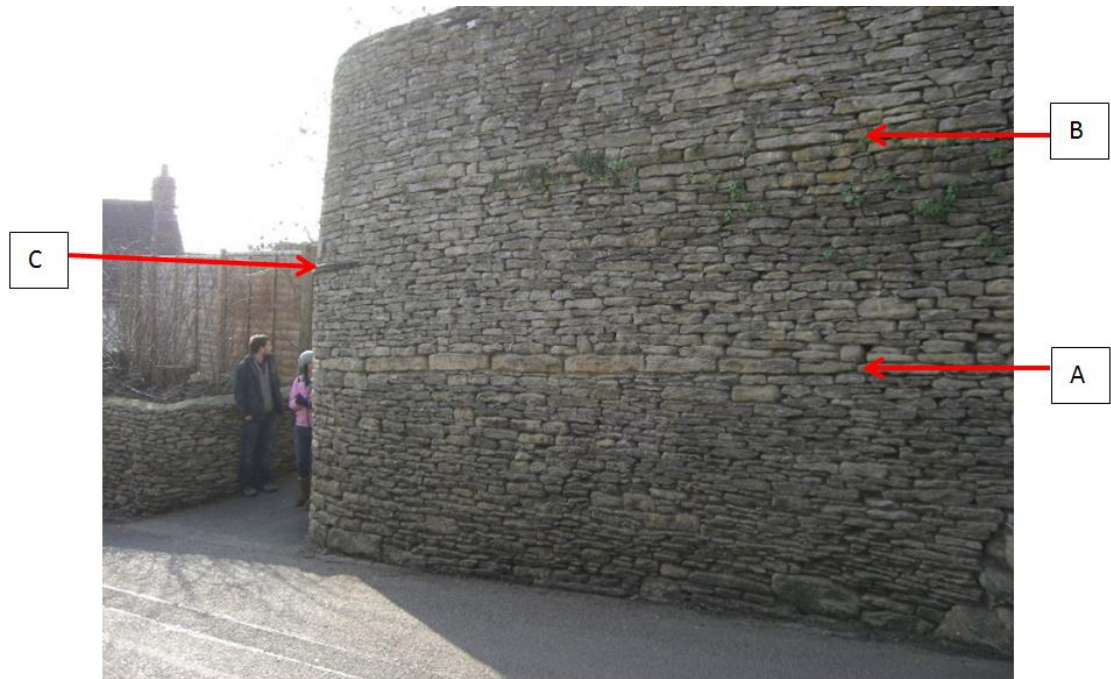


Figure 3.2: Garden retaining wall, Sherston. Retaining wall to garden above, approximately retaining for two thirds of height. This wall is unusually straight at its face with little batter, with two distinct bands of regular stone (A and B). There is also a tie plate to the corner of the wall (C) shown more clearly in Figure 3.2a

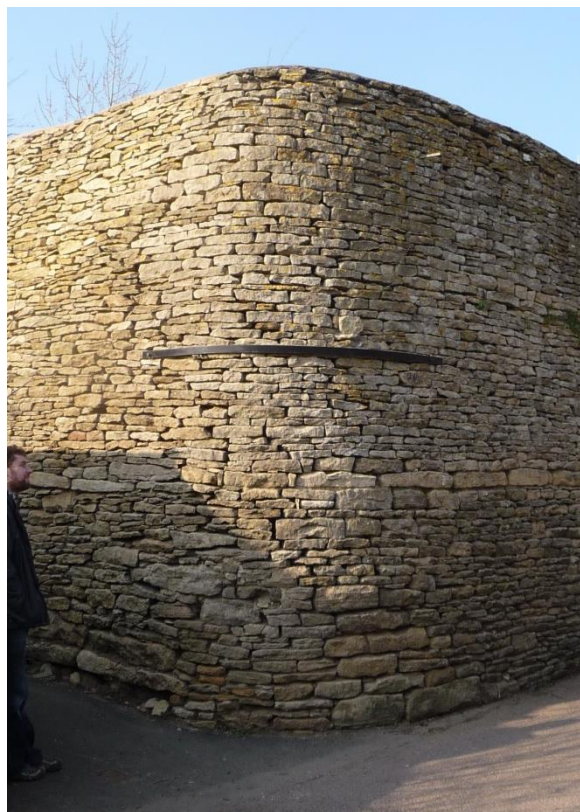


Figure 3.2a: Wall tie to corner of wall shown in Figure 3.2.



Figure 3.3: Garden Wall, Sherston. This wall is in a similar location to that in Figure 3.2, again abnormally straight with little batter. The bottom 10 courses (approximately) of this wall have been mortared, presumably to stop degradation from de-icing salts.

The walls in Figures 2.2 and 2.3 both retain gardens immediately adjacent to the road in Sherston, Wiltshire. These walls are in excess of 4m in height with a parapet, and retain gardens behind. They show a number of modifications and alterations, along with historical repairs, such as the tie band that can be seen on the corner of the wall in Figure 3.2. They also show signs of extensive pointing and mortaring, particularly to their bases as seen in Figure 3.3; this is a common modification to drystone walls, which could be carried out for a number of reasons. Due to the proximity of the road, it is likely here it is to prevent damage from salt spray from the road. However, mortaring of the wall in this way can prevent the free flow of water through the wall and create a build-up of water pressures, which can be detrimental to the wall's stability. However, at the time of visit these walls showed very little signs of distress or movement.

Figure 3.4 shows a wall constructed in a vertical style in Brompton Regis, Somerset. This wall construction is localised within this area and is specific to this stone type. The walls in this area are built very much in the fashion of stone banks, with definite rows of stones on end. Discussion with a local builder and repairer of these walls indicated that the wall construction is predominately long single stones that span into the backfill; this

was confirmed by inspection through voids. A number of stones within this wall appeared to be loose.



Figure 3.4: Vertical Construction, Brompton Regis. This is a wall typical to this location. Construction is typically only one stone deep with the longer axis of the stone into the wall. Some stones within the wall are relatively loose and can be moved by hand.

The section of wall in Northleach, Gloucestershire illustrated in Figure 3.5 is part of a larger wall that supports the main road into Northleach from the A40. This wall has a variety of styles within it most likely due to historic repairs. At the time of initial inspection, the section immediately adjacent to this image was under reconstruction due to a collapse (Figure 3.6). This highlights the need to be able to assess these structures, as during the repair the road above was shut for a prolonged period. Unusually this wall, due in part to previous research carried out in this area, was rebuilt using drystone, with the addition of soil reinforcement within the retained fill and connected to the drystone structure. This wall also shows areas of severe weathering, as can be seen in Figure 3.5. This weathering did not appear to be effecting the wall stability and in a number of places, redistribution had occurred round the contacts, which would not be able to occur if movement were occurring. A large section of this wall was later used to trial thermal imaging, as described in Chapter 7, including the new section.



Figure 3.5: Wall Section, Northleach. This section is immediately adjacent to a section of wall that collapsed. Stones in this area show a high amount of degradation. However, despite the adjacent collapse this section showed no signs of deformation.

Other than the stone colour, definite horizontal construction, and flat stones used to construct these walls, the main distinguishing feature of the majority of the walls is the angle at which stones are placed, typically around 12° from horizontal, towards the outer face. From discussion with wallers, these Cotswold walls are particularly prone to damage and material loss through water ingress into the wall, and through freeze thaw action. When walls are dismantled for reconstruction it is generally expected that only around 60% of the original stone can be reused, with the fill particularly prone to degradation. The 12° angle aims to promote water falling away from the wall to reduce water penetration. This form of construction is almost exclusive to this area, and goes against the general advice that stones should be placed either level or slanting slightly into the wall, to assist with stability



Figure 3.6: New wall under construction. This section of wall at Northleach collapsed and was under reconstruction, unusually using drystone. The section is noticeably wider than the original sections that can be seen either side of the repair, and has soil reinforcement in the retained fill.

Slanting the stones out in this manner has implications for stability. However it is only due to the high frictional properties of the stone, (as shown in Chapter 5), that the wall is able to resist the forces acting upon it. If built this way, the rear skin of the wall will also be sloping into the backfill, thus providing extra resistance to sliding forces.

The weathering of the stones was observed in a number of the older walls, particularly in the older section on the walls in Northleach. Here the stone weathering predominantly occurs around the contact points of the stones, leaving small pillar like features. Re-deposition of material was also seen at joints fusing the contacts – though likely to be brittle these features do demonstrate that these sections of walls are stable, as any movement would not allow weathering to occur in this manner. The re-deposition of material may also aid the resistance of the contacts.

3.2.2 Cornwall

Cornwall was chosen for its diversity of stone types as well as its diversity in styles. A number of the retaining walls in this area are also used around the coast as harbour walls and part of coastal defences. The stones around Cornwall varied from slates and shales on the north coast to granites in the southwest peninsular. The walling styles also varied in accordance with the stone type and use. The location of walls studied is in Figure 3.7.

The walls in Cornwall were predominantly of vertical and random construction, with both styles being found in coastal features. Some horizontal and herringbone constructions were found above water lines (Figure 3.8), in garden features and in the traditional Cornish banks. (Figure 3.9)

The vertical style was mainly found along the north coast and was associated with constructions formed of slates. This area is known for its slate, with the well-known Delabole slate quarry nearby, from which the slate is recognised for its extreme durability and can therefore remain serviceable for over 100 years. This durability makes slate from this area a good walling material, particularly in the harsh tidal environment. The slate used in these walls was very smooth sided and comparatively thin, with rough edges that were not worked other than at the face (Figure 3.10). This style of construction was also found in non-coastal structures, along with some horizontal and herringbone construction, the latter being generally for non-critical structures. The vertical construction was very well packed with no spacing between the stones. It was also possible to see the top of some walls and this tight overlapped construction could be seen throughout the width of the wall (Figure 3.11).

Random construction was predominantly found in the southwest, where the principal stone type is granite. Walls were often formed of rounded boulders giving an open construction (Figure 3.12).

Many of the walls, particularly next to the coast, had mortared faces as seen in Figure 3.8 along with Figures 3.13-3.15.

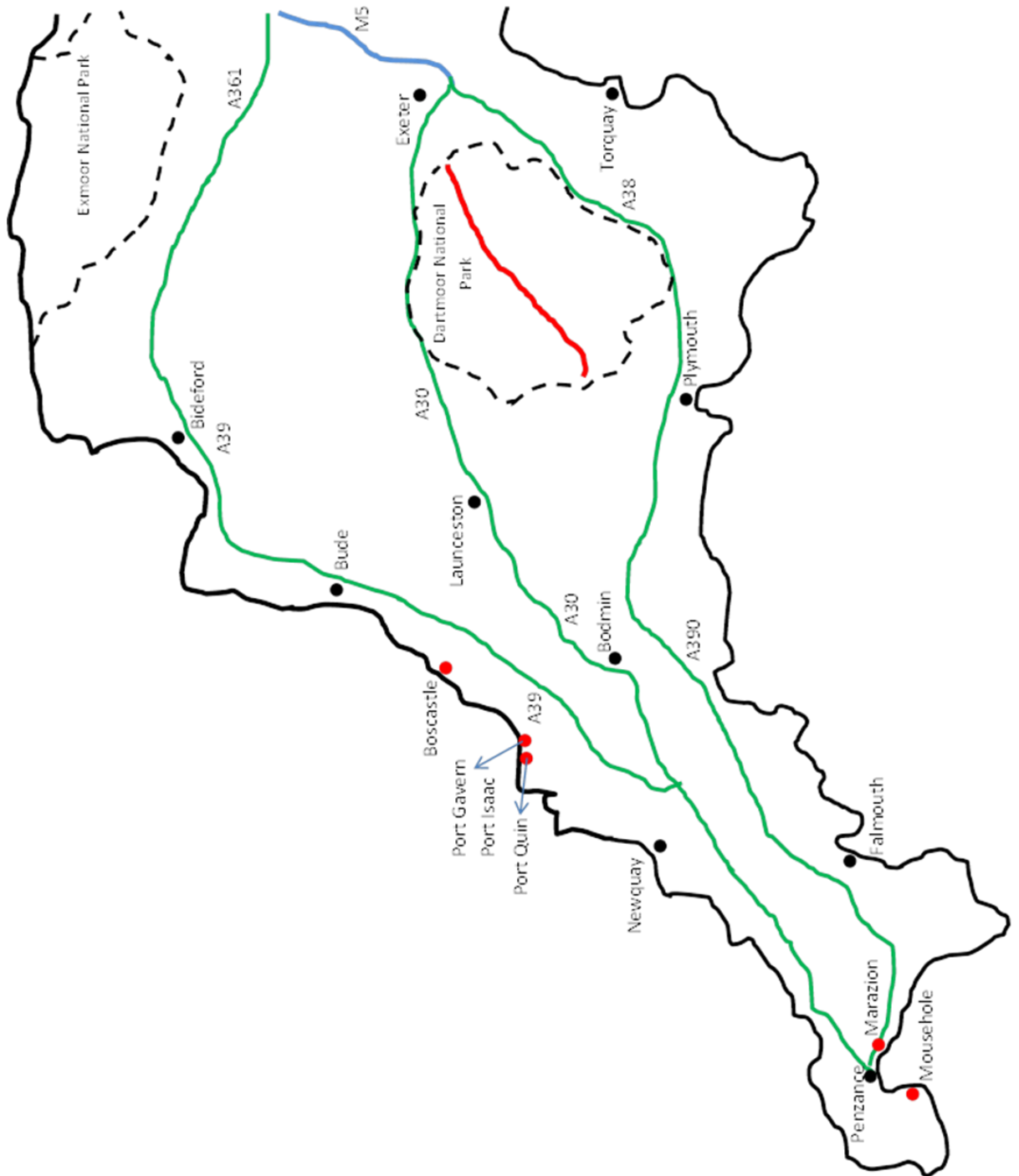


Figure 3.7: Map of Cornwall



Figure 3.8: Harbour wall, Boscastle, Cornwall. This image shows the variation in construction above and below the water line. Below the high tide mark construction is vertical and above the high water line the construction is horizontal. Much of the horizontal construction has also been mortared.



Figure 3.9: Herringbone wall in Boscastle, Cornwall. Herringbone construction is widely associated with the West Country and Cornwall in particular. Mainly used in Cornish banks such as in this image, where only small amounts of soil are retained. Often perceived as more decorative than other constructions.



Figure 3.10: Vertical slate construction, Boscastle, Cornwall. This is an estuary wall in the tidal region, typical of the walls lining the river throughout Boscastle.



Figure 3.11: Construction through wall, Boscastle, Cornwall. Image shows potential depth of these walls and how stones are placed throughout the wall width to form a continuous construction, mimicking the overlapping normally seen at the wall face. Also shows the size of some of the individual stones.



(a) General view



(b) Open wall structure

Figure 3.12: Open random construction, Mousehole, Cornwall. Constructed using large granitic boulders, this wall has a comparatively open structure with large gaps between the stones (b); it is assumed these aid dissipation of wave energy.



(a) Face of wall



(b) View behind mortar

Figure 3.13: Mortared wall face, Mousehole, Cornwall. This wall has been pointed at its face. In places this has been broken away, and stones have moved (a). The drystone construction can be seen behind the face (b).



(a) Intact wall



(b) Wall collapse following storms – taken March 2014

Figure 3.14: Mortared wall, Port Gavern, Cornwall. Much of this wall section is mortared. In February 2014 large storms hit the Cornish coast and this section of wall collapsed (b). The area of collapse seems to coincide with the visually different area to the centre of the original image. This wall forms a retaining wall to the back of a small bay directly facing the sea, forming the main protection to the road and houses beyond. It is mostly above the high water line.



Figure 3.15: Mortared wall, Port Quinn, Cornwall. This wall is fully mortared, as were all the walls in this bay. These walls face directly to the sea as at Port Gavern, and form the main protection to a number of properties. Mostly above the high water line.

The coastal structures in both areas were generally constructed using stones far larger than you would expect if used in other settings. Further walls in this area can be found in Appendix 1 along with further storm damage images.

3.2.3 Ffestiniog Railway, North Wales

The Ffestiniog railway area was studied due to the unusual use of drystone retaining walls to form large embankments throughout the length of the railway. The sheer scale of the walls and the size of the stones used are unusual within current UK walling stock.

The original railway was constructed in the early 1800s as a means of transporting slate from the quarries in the mountains to the port of Porthmadog. The railway was built on a continuous gradient and was only just wide enough to allow a wagon and horse to pass. In the late 1800s the narrow gauge steam trains were introduced - this meant that various modifications were made to the railway. This included widening of the embankments to allow for the wider trains, which means that many of the embankment structures had additional layers of stone added onto the original face. The track has also been moved in places to reduce the tight curves that the horses were able to negotiate but not the trains. The railway was shut in the 1940s and remained derelict for a number of years. The railway now runs predominantly as a tourist line and a number of

works have been carried out over the years, including the refurbishment/replacement of a number of culverts that run under the embankments and the repair/rebuilding of a number of the smaller walls.

There have been some notable large wall failures, predominantly induced by high rainfall and ground water. However, the majority of the large walls along the railway appear to be in good condition with little to no movement. A number of the walls have been historically buttressed (Figure 3.16) and these are a prominent feature along the railway. These buttresses are typically dome topped, and do not appear to be tied to the walls; they typically extend for relatively small sections of wall. The railway has stability issues with their smaller walls (1m in height or so), which is attributed to a lower build quality, suggesting that master craftsmen were employed for the larger more critical walls.



Figure 3.16: Buttress example, Ffestiniog Railway. This shows a typical buttress example built up against the face of the embankment with either a domed or flat top. At this section, the embankment is two sided and cuts through a wooded area. It has been known for the area behind the embankment (LHS image) to flood during wet periods putting additional forces on the structure.

Another issue the railway has with some of their walls is that the exposed bedrock on which they are constructed is eroding, thus removing the foundations of the wall, and potentially causing them to fail. The railway has put remedial measures in place to help prevent this, which nominally consist of hardened cement bags against the face of the rock (Figure 3.17).

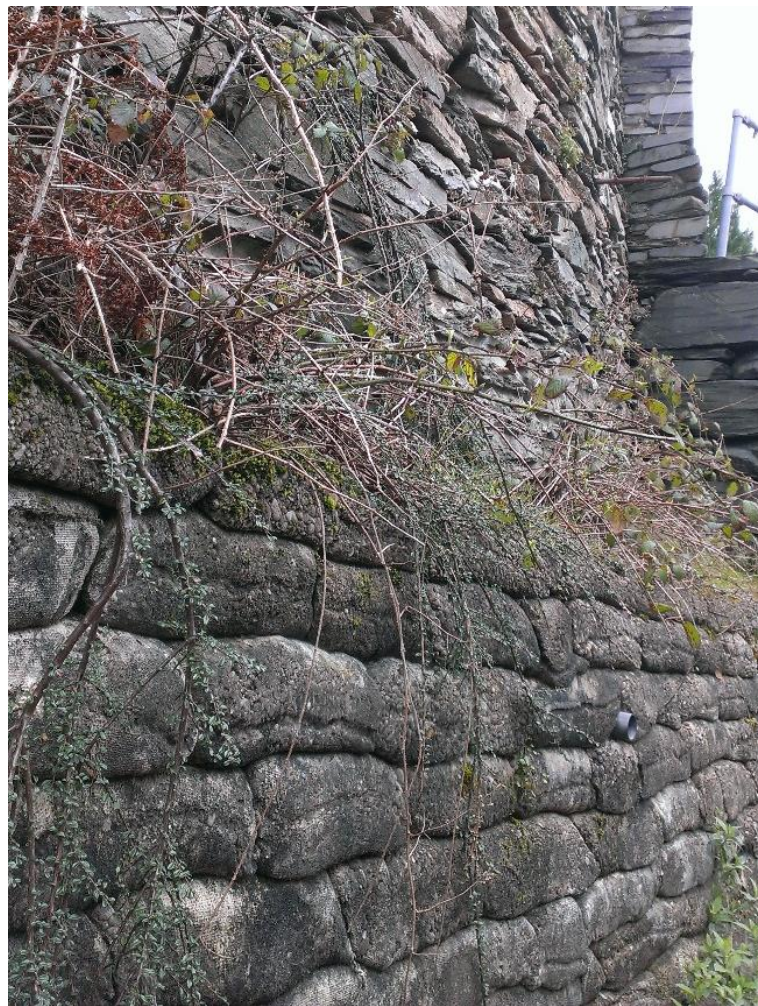


Figure 3.17: Foundation protection, Ffestiniog Railway. In areas particularly toward the top of the railway in the mountains, the embankment walls are constructed directly onto the bedrock. Here the issue is that the bedrock is not of such good quality as the wall above it and is degrading, endangering the wall. To alleviate this and to protect the bedrock below, sandbags of cement have been stacked against the bedrock face and allowed to cure. This contains the degrading bedrock as well as preventing further erosion.

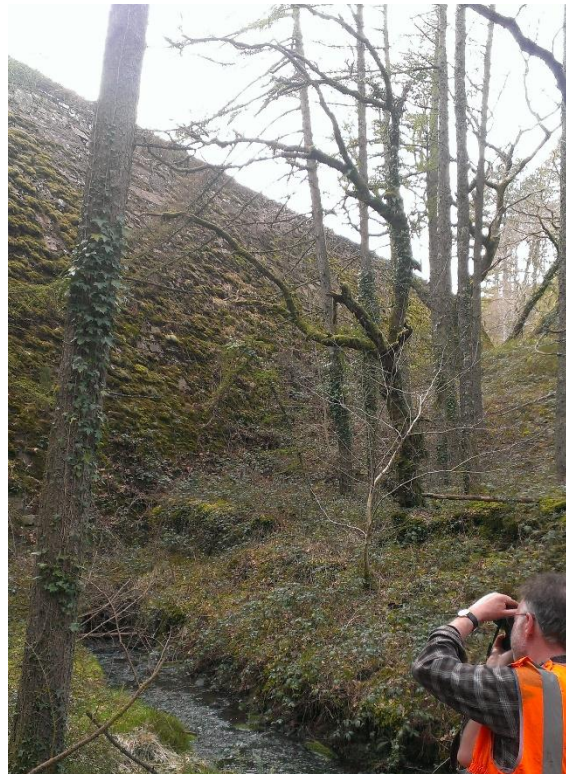
Stone for the wall is predominately of a slate like nature, which is readily available in the area and often of a very large size. The stones used vary between rough edged stone, probably of a lesser quality not wanted for export, and finer worked stones with a defined shape. These two types do not appear to be mixed within a single wall.

A number of walls were studied during the visit, mainly dictated by available access. A selection of these are described below:



Figure 3.18: Supporting Wall on A497, Ffestiniog Railway. The railway runs directly behind the wall, which was reconstructed following a major collapse in the 1980's.

The wall in Figure 3.18 supports the railway on the A497 on the outskirts of Minffordd. The stones used to construct this wall like much of the railway are significant size. This wall is built on sand, and had problems due to subsidence prior to the late 1980's and early 1990's, when a drainage scheme was implemented. There was also a major collapse in the 1980's due to high water both sides of the wall, due to rainfall and high tides, along with vibrations from passing lorries. However, this collapse was not as bad as it may have been due to slumping of the outer wall, which restrained the old inner wall allowing it to simply drop vertically. Since the implementation of correct drainage, there have been significantly less problems with the wall.



(a) Image from North side at ground level



(b) Image from Western end at rail level

Figure 3.19: Cei Mawr, Ffestiniog Railway. Reputedly, the largest drystone embankment in Europe it stands approximately 19m high with a continuous curve. It is completely freestanding, with a stream running under it (as can be seen in image a) through a culvert in the base. It was buttressed to the North East and South East in the late 1800's

Cei Mawr (Figures 3.19) is reportedly the largest drystone embankment in Europe (Festrail, 2017). This embankment is entirely free standing and is constructed on a curve as can be seen in Figure 3.19b. From the face, it appears to be constructed as a large freestanding wall, and probably contains some of the largest stones on the railway by face size. There are culverts running under the embankment, as with many of the other embankments, to allow water to pass.

These walls are constructed using very large stones and pose questions about their construction. One wall in particular had a number of issues – however, it was not possible to view this wall closely as it was built on private land (Figures 3.20 and 3.21). This wall is curved, as are most of the other walls, and situated directly next to where the railway crosses a road. Some previous works have already been carried out on this wall to rebuild the top section. In Figure 3.21 tie bars can be made out protruding from the wall which show where the wall line was prior to repair.



Figure 3.20: Unstable wall, Ffestiniog Railway. This section of wall is adjacent to where the railway crosses a road. It appears particularly unstable and is of concern to the railway. The issue here is access as it is one of the few walls facing onto private land. Due to the access issue, unfortunately this wall could not be investigated fully as part of this research. Some historical repair has been carried out as seen below.

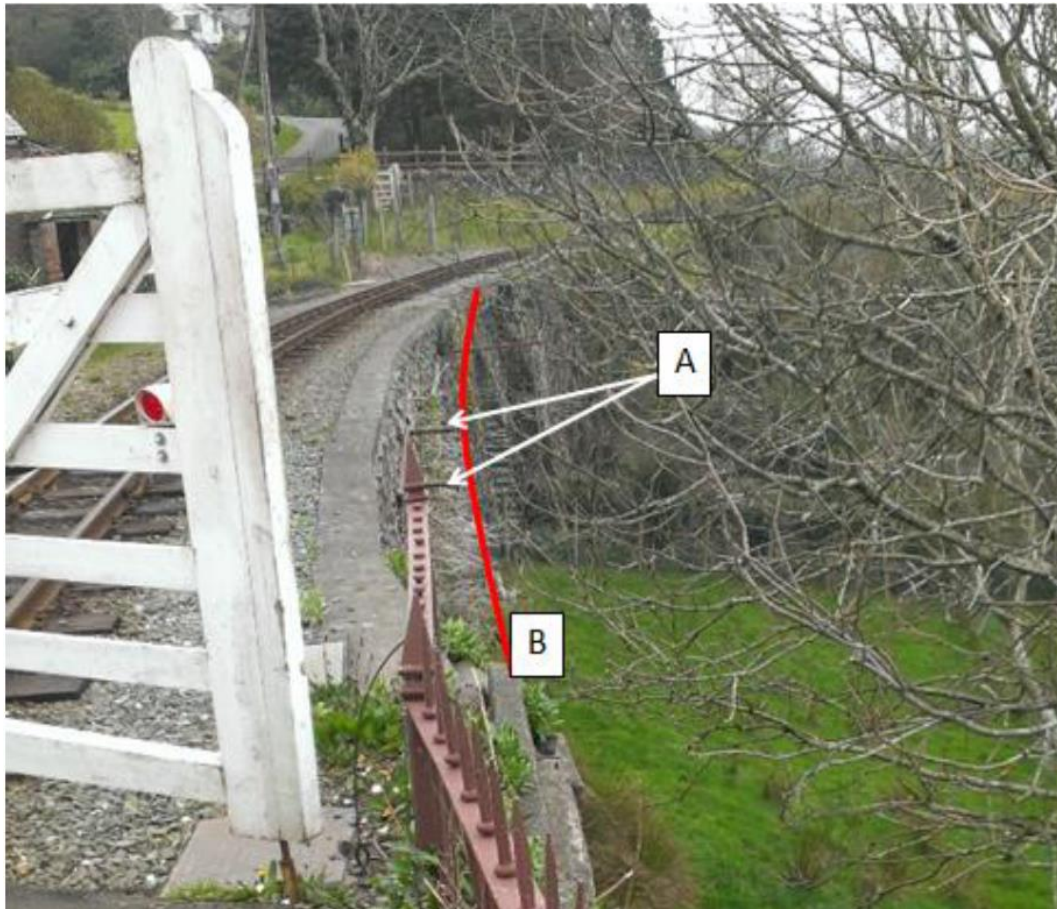


Figure 3.21: Unstable wall realign, Ffestiniog Railway. This is the wall in Figure 3.20 from above, taken from the road where the railway crosses. Here you can see the old tie bars (A) that were inserted to keep the wall stable prior to previous works. Approximate line of original wall shown (B).

Construction here is predominantly slates, from the slate quarries the railway line was built to service, as well as from the large amount of slate found at the surface. Visually this slate is not as fine as the slates seen in Cornwall and potentially not as high in quality. The individual stones are also more blocky than found in Cornwall, and are constructed horizontally. The freestanding embankments are potentially built as if they were freestanding walls in their own right.

3.3 The Cevennes, France.

The Cevennes area of France was selected for the study due to the varied local geology in a relatively small area, enabling walling to be constructed using a number of different materials within this region. This area and the wallers have also been involved in significant drystone research in France, unlike in the UK

In this area of France retaining walls are the main drystone feature due to the mountainous nature of the area, unlike in the UK where they are field walls. Due to the terrain and as a result of their involvement in local research, the wallers in this area have a significant intuitive technical knowledge about the construction of retaining walls.

The walls in this area are used for a variety of circumstances – mainly to retain roads or terraces. Some of the walls studied are also liable to flooding at certain times of year. As well as historic walls, there are a greater number of new walls, built within the last 10 years, than compared to the UK.

Some of the walls seen in France are described below. Further images from this region can be found in Appendix 5 where they were studied in relation to thermal imaging.



Figure 3.22: Map of wall locations in France



Figure 3.23: River wall St Enimie, France. This is a modern wall around 4m high constructed from limestone. Situated directly next to the river it is subjected to annual flooding, which can be of significant height. It shows no sign of distress.

Compared to the walls seen in the UK the wall in Figure 3.23 is relatively modern. St Enimie is prone to flooding of significant depth. The wall has withstood floodwaters with little evidence of damage, it is likely that this will be a recurring event throughout the life span of the wall.

Figure 3.24 shows the oldest wall seen in France. This wall supports a sharp bend in the road and has become deformed over the years, causing it to be buttressed in places. The French wallers were keen to show us this wall due to its age, as well as to discuss the changes in building practice. In this area, historic walls were constructed with a flat back forming a wedge shape. Modern walls are constructed using a stepped back. This not only reduces the amount of material required but makes use of the earth pressures acting on the back of the wall to aid stability.



(a) Looking east along wall



(b) Looking west at incoming bend and buttress

Figure 3.24: Historic wall supporting D998, France. This wall is constructed directly off the bedrock below to cross a river valley around the mountain. The forces this wall are subjected to are unusual due to the tight curves both of the wall and a tight opposite hand bend, prior to the wall to the west, and the subsequent forces induced by vehicles. The wall is buttressed to the west (A) to help resist these forces.



Figure 3.25: Training wall, walling School, France. Amateurs constructed this wall as part of a course. While not as neat or as visually pleasing as the professional wallers would like, it is perfectly adequate structurally and still follows the main construction principles.

The wallers in France have also set up a walling school where novices and professionals alike have the opportunity to learn new skills and learn from each other. The wall in Figure 3.25 is such a wall built as part of the walling school. This wall is not as visually pleasing as many of the walls seen in France, which may be taken as a sign of lesser quality and hence stability; however the wallers although not satisfied with how it appears visually, concede that structurally it is still sound and more than adequate for its job.

The majority of the walls observed in France were built of horizontal construction with some random construction. Horizontal construction were mainly associated with limestone and shale constructions, whilst the random construction was associated with granites. The walls in this area were constructed in a more continuous manner with larger stones overlapped throughout the width of the wall, with no fill. Larger through type stones are present in this construction. However, these are not always specifically built in (as found in UK walls) as they are not required to tie the wall together in the same way. Through talking to wallers, it was discovered that they also place stones leaning back into the wall towards the backfill. As well as aiding resistance to sliding, this also enables any water that enters the wall to reach the backfill and drain away as quick as possible. Any stone chips and rubble are also often placed behind the wall in order to aid drainage, which is also a common practice in the UK. This approach is also

said to prevent the rear of the wall becoming clogged with soil and causing water pressures to build behind the wall.

The limestone here is much finer and more durable than that seen in the Cotswolds. The individual stones are also much larger, enabling the walls to be constructed in the manner seen. The scale of the retaining walls seen in the Cevennes area varied from 1-5m in height.

The French wallers are also experimental with their walling and often add decorative features. Roland Mousquès is particularly well known for this, and his walls include many features, such as faces or decorative bands of the same material. Some walls are built of mixed materials, depending on what is available, and are included in Appendix 1.

3.4 Construction Theories

From studying these walls, it is possible to see the variations in style both locally and on a wider scale. It is also possible to see how stone type and geometry has an effect on the construction styles of the wall. There are significant differences within styles dependant on local techniques, as well the more subtle differences between wallers. These subtle differences need to be acknowledged and it may be possible with further study to identify individual wallers by how they construct. However, this is not a concern of this study. The regional differences are more important to investigate, and how these have come about through many generations of wallers.

Horizontal walls appear to be primarily built with either smaller stones that have high frictional properties, such as in the Cotswolds, or from larger more blocky stones with straighter sides that could not easily be interlocked if built vertically. Where these stones are larger, walls can be built horizontally with lower friction stones, as their weight aids resistance to movement. At the wall face, horizontal construction often appears as a very tight form of construction. However, as seen in Cotswold walling, these stones can taper away from the face creating voids behind the face. A well-packed fill and suitable pinnings will help reduce this void. However, it should not be assumed that what is seen at the face would continue throughout the wall.

The vertical walls are primarily built of thinner pieces of stone with rough edges that are not necessarily straight. These are also stone types that may not respond well to being

worked to create the straighter edges preferable for horizontal construction. The stone used is primarily smooth lower friction stones such as fine slates, and in a range of sizes. However, a single wall will tend to have stones of comparable size within it. Vertical construction is also common in tidal situations. Vertical construction, as described below, is a very tight construction and is likely to have less voidage than the other construction methods.

Random construction in its purist form is found where stones are unable to be worked. They are used as they are found and fitted together in their best configuration. Where these are rounded boulders, as in Mousehole in Cornwall, this produces a very open wall. However, if the stones are angular at the wall face these walls may appear to be very tight, though as with horizontal construction, it should not be assumed that what is seen at the face continues behind, since there is likely to be a high percentage of voids in the wall.

Tight construction at the wall face is driven by the need of wallers and the demands of clients to have a visually pleasing, neat looking wall. In further discussion with wallers they will agree that a wall does not necessarily need to be finished to such a high visual quality to still be a very effective wall. This is supported by research carried out in France by Colas et al. (2012) where the wall considered to be of lower visual quality was able to withstand higher loadings. It is the construction behind the face that has the greatest effect on the walls stability.

3.5 Conclusion

In well-constructed horizontal construction the stones overlap 2-on-1 1-on-2, as in a brick wall. This overlapping, combined with the frictional capabilities of the stones under the wall's self-weight, allows a tensile force to be carried along the length of the wall's face. This tension force can help support the classic deformed bulged, redistributing load from weaker sections to stronger sections. This type of effect can be akin to the interleaving the pages of two telephone books: friction between the sheets makes it very difficult to pull the books apart. Natural fibre ropes work in a similar way: the twisting of the relatively short fibres in the opposite direction to the twisting of the strands presses them against each other, so that a long rope can have high tensile strength even though it is made up of short fibres simply pressed against each other.

(McCombie et al 2012). The combined frictional properties allows this style to be constructed using the smaller high friction stones in a double-skinned approach, and the larger lower friction stones in a more continuous construction. This form of construction is highly reliant on the frictional properties or the weight of the individual stones, or a combination of the two.

Vertical construction is often continuous with the stones either spanning the entire width of the wall or overlapping through the wall. The longest orientation of the stone is usually into the wall. In this form of construction, wedging of the stones is used to prevent the stones from moving within the wall and to create a compressional pre-stressing within it. In order to do this, the ends of the wall need to be well confined. This pre-stressing helps the stones to resist forces, as it is much harder to force the stones out of the wall – very similar to picking up books by compressing the ends. As with the horizontal construction, the stones are also overlapped in the vertical direction, allowing the pre-stressing forces to create tensional forces over the height of the wall. It is probable that if a wall constructed in this way failed, it would be more explosive than a horizontal wall.

Random construction is unlikely in its purest form to have the mechanisms described above, relying mainly on the frictional properties of the stone and the mass of the individual elements. The stones typically found in these walls are hard to work and are often granitic type materials that have high frictional properties and densities. Where there is crossover between the styles you would expect there to be some of the mechanisms found in the other styles.

Different styles all have different mechanisms within them that enable each wall to work as it does and transfer loads efficiently, with inherent flexibility. Styles often reflect particular stone types and the mechanisms involved aid the properties of the stones within the walls. Local variations also reflect particular properties of stones and appear to mainly revolve around water shedding and dispersal.

Harbour walls also seem to have a defining vertical style. This verticality not only aids water shedding from the wall, but the stones are also less likely to be affected by uplift from wave action due to having a smaller horizontal surface area. Other harbour walls

with a more open random structure are likely to help dissipate wave energy, reducing the damaging impact of the waves.

Chapter 4

Council Study

4.1 Introduction

With the majority of the existing drystone retaining stock supporting roads or ground above roads, many come under the care of local councils, who are responsible for their upkeep and management. As such they need to be able to assess these structures to enable informed decisions to be made regarding their current status, and future actions to be taken.

As part of this study two council highways departments, Gloucester and Cornwall, each with differing approaches to the issue of drystone walls on highways. Visits were carried out to discuss how the issue of these walls is dealt with and their current assessment methods, as well as to see how this may be aided by any additional tools provided.

4.2 Assessment Methods

While visiting the councils as well as talking to them about how they go about assessing these structures, a number of wall reports were collected which were specific to drystone, to see what information is collated along with the standard report format.

It was found that the two areas have different approaches to the issue of drystone retaining walls, mainly developed from issues of costs. Gloucester highways have a reactive approach and do not necessarily know about a wall until it is reported to them by a member of the public as requiring attention or looking at. While this approach

helps reduce costs, when an engineer goes to investigate a wall there are no previous references as to its condition or appearance, potentially making assessment harder. Cornwall on the other hand has a proactive response to these structures. Due to the lack of other large highway infrastructures, approximately 5-10 years ago funding was gained to enable then to actively find retaining structures and make detailed records of them. This approach means if any issues are reported regarding these structures they can be compared to the information gathered previously and a judgment made on its current condition. In both cases drystone is not separated from other masonry or gabion retaining structures and all are assessed in a similar manor using the same format.

A summary of the information gathered by the councils and report format of both councils is shown below. The number of reports gathered also gives an indication as to the number of walls with the areas covered, however the actual number is expected to be greater than this. For example, Gloucester do not keep all their reports in electronic format, also as stated above neither council keeps drystone reports separate from non-drystone retaining structures so the reports were searched for manually and therefore it is likely some were missed.

An example report from both Gloucester and Cornwall can be found in Appendix 2.

4.2.1 Gloucester Reports

In total approximately 80 reports were collected from Gloucester. Generally most of the reports follow the format described below, however some consist of just a brief description/sketch and photos of the wall in question. Typically the reports are less than 10 pages in length. As well as documenting the wall the purpose of visits made by Gloucester is also to ascertain who is responsible for repair, based on the situation of the wall.

The majority of the reports contain the following section:

- General wall details, including: height, length, what it retains in relation to the highway.
- Construction details, including: if the wall is drystone or not, general description of wall, and mortar present, if it has copes or a parapet.

- Wall condition, including: areas of deformation, areas of collapse, any bulges or movement present, presence of trees and other vegetation, and a general appearance of wall surface. This section appears to vary in detail with some reports have a more descriptive overview and others having a tabulated set of recordings with detailed measurements.
- Recommendations for repair/replacement. If other parties are likely to be responsible for this this is also stated.

The written report is typically followed by photos of the wall and its defects.

Additionally, some reports also contain sketches of the wall face. None of the Gloucester reports appear to contain any structural analysis as it is not deemed possible to ascertain with any certainty the capacity of these walls but is rather down to personal experience and judgement.

Typically repair options do not include replacements using drystone but an equivalent masonry of concrete solution. This can include recommendation on the stone type and colour to be similar to that existing. Also invariably unless imminent works are needed it is typical that the walls continued to be monitored until works are essential.

4.2.2 Cornwall Reports

Due to the reduced number of major highway infrastructures Cornwall have been able to fully record the majority of their retaining structures to enable a comprehensive database to be formed. This not only allows them to know what structures are in their care but also if issues of one of these is reported then they have a good reference point to refer to when making a new assessment of the structure.

In total 133 were collected from Cornwall. Typically these reports are 20-40 pages long. The Cornish wall reports typically contain the following:

- Visual assessment of wall and road above (if required) detailing and defects found
- An analytical assessment of the wall structure using suitable highways codes of practices and loadings. The codes used can vary between reports and occasionally the theory proposed by Cooper (1986) on drystone stability is used. This assessment often assumes a conservative initial thickness and if this is

deemed not to be suitable the thickness required is calculated and a judgement made on whether this is reasonable given the wall condition.

- Details such as wall height, length and batter are recorded.
- A detailed sketch of the wall elevation is typically included showing measurements, an idea of construction, critical dimensions, defects and vegetation, along with a basic section.
- If any previous reports are present for the wall
- Monitoring requirements
- Photos of the wall and any defects.

4.3 Conclusions

Although the two councils have different approaches in dealing with these walls they both use visual inspections in order to gain an assessment of the walls stability. This relies mainly in the knowledge and experience of the engineer involved, as well as potentially that of colleagues in discussion. Where an engineer has had many years of looking at these structures it may mean that a fair assessment of these walls can be made. However if an engineer has less experience in these structures, it is likely that judgments made about the wall will not be a true representation of its current structural state. The assessment of these structures is also known to be tricky even with years of experience as they can behave in unexpected ways, with even the most experience wallers coming across situations, such as when dismantling areas that are obviously in need of repair, further sections have unexpectedly collapsed that appeared to be stable previously.

Wrongly assessing these structures can lead to two potential outcomes: walls are replaced unnecessarily with a non-drystone solution that is often not in keeping with the area, or no works are carried out leading to failure that potentially closes a road and causes damage to neighbouring structures. Both of these also have cost implications to the council involved.

From talking to both councils they understand the difficulties in assessing drystone retaining walls compared to mortared constructions, and often it appears no detailed numerical analysis is carried out, relying predominantly on engineering judgment and maybe some basic hand calculations to get a feel of the general limits on overall

stability. From this it appears any additional tools that could aid in assessment are likely to be welcomed if it enables the engineer to gain a better perspective on the structural make up of a wall. If the basic features of the wall could be identified and measured e.g. wall width this would help aid assessment as a gravity retaining structure. Also identifying the features associated with good construction practice would allow judgements to be made regarding the quality of the general wall construction.

Assessments are often carried out by one person alone, and there is also a potential for time constraints as well as limited access. Therefore any tools provided would need to be compact and able to be used by a single person, as well as being easy to use and not add significant to the time spent at a site.

Chapter 5

Initial Study on Friction

5.1 Introduction

As has been discussed in previous chapters, the stability and ductility of drystone retaining walls is critically dependent on the friction between individual stones. Investigations of stone on stone friction have previously been reported in conjunction with all recent full-scale test programs (e.g. Villemus 2007; Colas, 2009; Mundell 2009). In 2011 (Warren, dissertation) an initial study was carried out to investigate wall constructions around the Cotswold area, as well as to look the frictional properties of the stones used to construct them. As part of the present work, this testing has been examined in more detail, because it considered the effect of dilation on friction angle. This is important because it examines differences between stone types (e.g. rough limestone and smooth shale), and so must be understood before the relationships between stone types and construction styles can be properly understood.

Due to the lack of mortar within the wall drystone construction relies on a combination of self-weight and stone frictional properties for the stability of the wall. Within all failure mechanisms stone on stone movement needs to occur; how that occurs and when are likely to be down to the frictional properties of the individual elements. A number of shear box and tilt tests were carried out on limestone and Morte slate originally used in the construction of Mundell's (2009) walls.

The type of stone and its frictional properties, and the size and orientation of the individual stone elements, can affect the stability of the wall. During wall construction,

stones with flat surfaces are often angled either into the wall to aid stability or out of the wall to aid water run-off. This angling of stones out of the wall is particularly common in the Cotswold area in the United Kingdom. Orientating stone in this way favours sliding driven by earth pressure on the back of the wall, increasing the demand on the frictional strength of the stone surfaces. Though post-construction wall movement will mostly consist of small translations, small rotations may also take place which could increase the outward inclination of some stones. The weathering of the stone also affects the wall stability as it can cause degradation of individual stones. The products of the weathering may be lost from the wall due to rain or wind, reducing the overall mass, or they may remain in situ, in which case the altered minerals are likely to have a lower strength.

As part of a field study, methods which would allow stone angles within the wall to be measured and recorded were investigated, in order to give an over view of the wall construction. Movement within the wall may cause the outward slope of the typical Cotswold construction to become exaggerated or cause walls originally constructed with the stone sloping back to have forward sloping stones. The closer this slope angle is to the friction angle of the stone the less residual capacity it has in resisting load.

Laboratory testing and field measurements were used to investigate the frictional properties of individual elements within drystone retaining walls, to document construction styles within distinct geological areas, and to compare these with particular regard to stone shape and orientation.

By combining frictional data to the construction overviews it can be seen if the individual elements within the wall are close to failure, and the effect this may have on the overall wall stability.

5.2 Literature Review

Stone friction is affected by the roughness of the stone at both microscopic and macroscopic scales. Zhang (2005) describes levels of roughness in regard to rock mechanics from the 'waviness' of a surface to small and intermediate scale roughness, ranging from kilometres to centimetres. The scale of surface roughness of the stones considered in this study ranges from centimetres to fractions of a millimetre. Zhang

(2005) shows three types of roughness profile: stepped, undulating and planar; with stepped and undulating being significantly rougher than the planar (Figure 5.1). This concept can be extended to describe the smaller-scale roughness of walling stone.

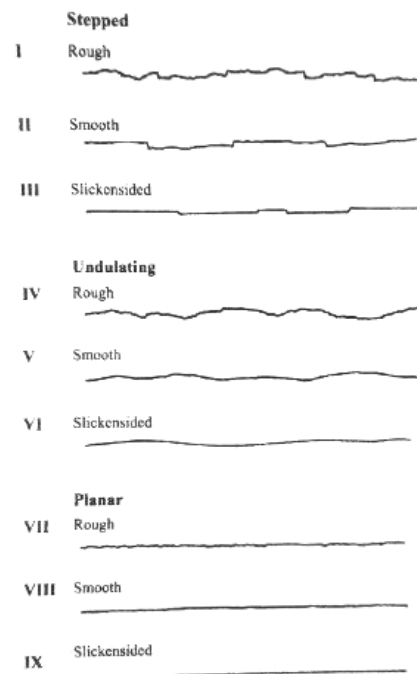


Figure 5.1: Zhang (2005) Roughness Scale

An alternate method of assessing stone roughness is suggested by Raouli and Harrison (2010). The normal vectors to lines connecting two points of the stone profile are used to create vector profiles, from which information about the roughness can be obtained. Stone roughness and roughness profiles alter between stone types and can be affected by weathering.

Roughness can lead to interlocking of joints as proposed by Walker and Dickens (1995), either immediately when the stones are placed or in subsequent deformation, which aids wall stability. Interlocking can continue to occur as the stones deflect, jumping and relocking as the stones continue to interlock, Figure 5.2.

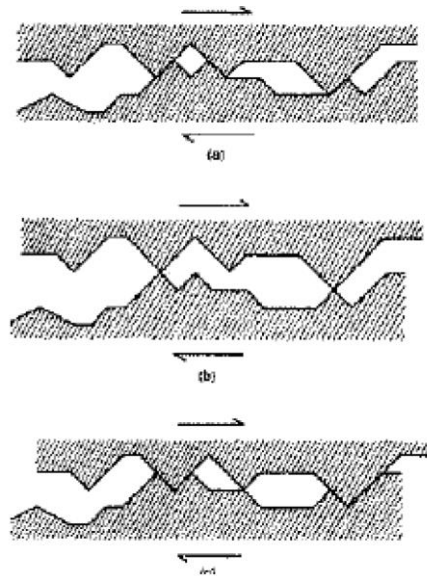


Figure 5.2: Stone Interlocking (Walker and Dickens, 1995)

Walker and Dickens showed this theory through a number of shear boxes test on granite purposely carried out with mismatched joints. During these tests large fluctuations were seen in stress levels during displacement. Other studies have also carried out frictional testing, including Mundell (2009) and Villemus (2006). Mundell used cut shear box tests along with tilt tests to determine the frictional properties of his stone. He also carried out shear box testing between the stone and the aggregate used to back fill his walls, to gain an idea of the friction mobilised between the backfill and rear of the wall. Villemus carried out testing using two layers of limestone as would be found within a wall, to test the shear bed strength, as well as using cut stone tests. Villemus found the cut stone test results to be very similar to those obtained from the stone beds, approximately 37° . Mundell also used limestone; however he found his average friction to be higher at around 46.4° . With Villemus' experiments the use of the layer of stone may be an issue as the stones move; although they were initially packed to ensure they had contact with the shear box and hence were loaded, as they move it may be that the stones become unloaded hence giving false results. In the current study it was decided to use a single pair of stones with the top stone being directly loaded via a plate to prevent this from occurring. Although the stone used was the same as used by Mundell it had been subjected to a further 3 years exposure and weathering, meaning the results gained were likely to be different from those of Mundell, as well as being potentially more representative of stones within an existing wall.

Work carried out by Ramana and Gogte (1987) also looks into how mineralogy of different stone types affects the frictional properties using simple tilt tests. They showed that the mineralogy of the rock had an effect on the frictional properties overall. From this it may also be assumed that if differences in the mineralogy can affect the stone friction as a whole, then there will also be local effects on the stone surface. As well as the type of stone and its frictional properties, the size and orientation of the individual stone elements can affect the stability of the wall.

Laboratory testing and field measurements were used to investigate the frictional properties of individual elements within drystone retaining walls, to document construction styles within distinct geological areas, and to compare these with particular regard to stone shape and orientation.

5.3 Laboratory Study

Samples of some of the stone types found in the field studies were tested to measure the surface friction between the individual stones. Tilt tests were carried out on a quarried limestone and a Morte slate, followed by tests in an adapted shear box on these stones and a weathered limestone. Whilst the stones were not extracted from in situ walls, the quarry stone was material supplied for wall construction, whilst the weathered stone was visually similar to stone in nearby walls, and subject to similar weathering conditions.

In the tilt test a pair of stones was placed onto a board, one on top of the other, with the bottom stone prevented from sliding (Figure 5.3). The board was then raised at one end until the top stone began to slide. In many tests the stone would move only a short distance and come to a halt, so the board was tilted to a steeper angle leading to the top stone sliding off completely. The angle of the board at both of these points, slide angle and failure angle, was recorded using clinometers (Table 5.2). In all tests the upper surface of the lower stone was parallel to the board. This was repeated three times for each stone pairing, and two pairs of stones were used for each stone type.

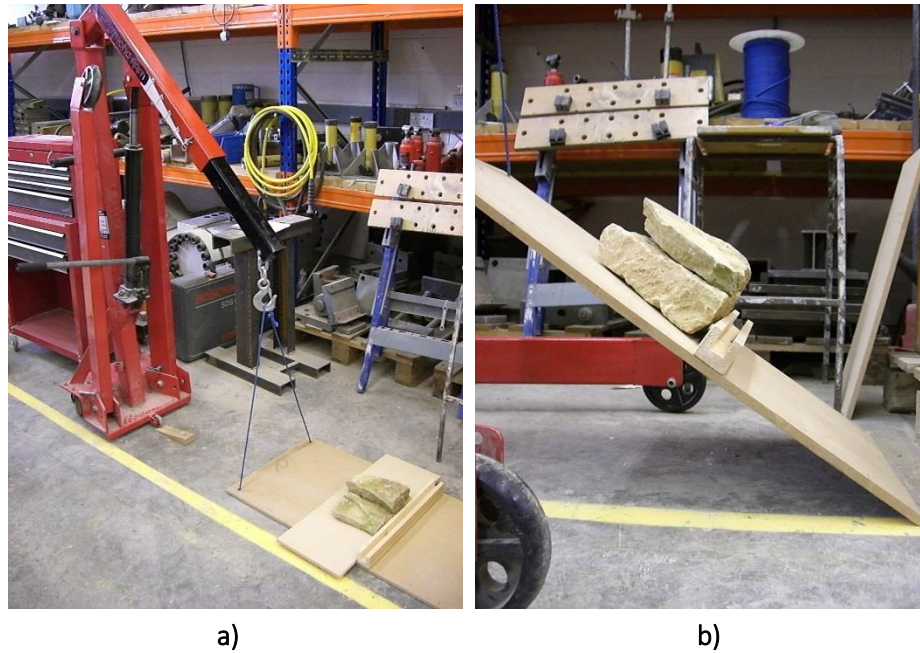


Figure 5.3: Initial tilt testing a) general set up, b) during testing

Procedures for a standard shear box test are outlined in BS 1377-7:1990 and ASTM D5607-08. BS 1377-7 deals predominantly with the testing of soils and ASTM D5607 the testing of rocks. In both methods both the top and bottom sections of the samples are enclosed within the shear box. After initial experiments it was found that enclosing the top stone restricted its movement - it could not rock or rotate as it might in a wall. It was therefore decided that the top stone would be placed directly onto the bottom stone without the shear box arrangement around it, to allow these movements to occur (Figure 5.4). A plate was then secured to the top of the stone to which the normal loading could be applied. The base stone was placed securely into the base of the shear box, and then displaced horizontally while the top stone was restricted from moving in this direction. Shearing was carried out under a number of normal loadings, as shown in Table 5.1, to represent different depths within the wall. Testing was carried out on two pairs of stones for each stone type.

Table 5.1: Initial Normal Loadings for Shear box Testing of Quarry Limestone, Weathered Limestone and Morte Slate.

Stone	Normal Loadings (kN)				
	Test 1	Test 2	Test 3	Test 4	Test 5
Quarry Limestone	0.94	2.36	4.73	7.09	9.45
Quarry Limestone	0.60	1.51	3.02	4.53	6.04
Weathered Limestone	0.90	2.25	4.50	6.75	9.00
Weathered Limestone	0.90	2.25	4.50	6.75	9.00
Morte Slate	0.94	2.36	4.73	7.09	9.45
Morte Slate	0.90	2.26	4.52	6.79	9.05

In the first experiments the horizontal displacement was measured offset from the loading point, a convenient arrangement using the conventional layout of the test. When the results were processed to relate vertical to horizontal movement, which was expected to correspond in some way to the undulations in stone surface, a number of spikes were observed. This was due to rotation of the stone during the test, associated with the offset of the displacement measurement. To remove this effect a number of the experiments were repeated with additional horizontal transducers to measure the displacement either side of the loading point, as well as over the loading point, thus providing both a redundancy in the measurement of displacement, and measurement of any rotation that took place (Figure 5.4).

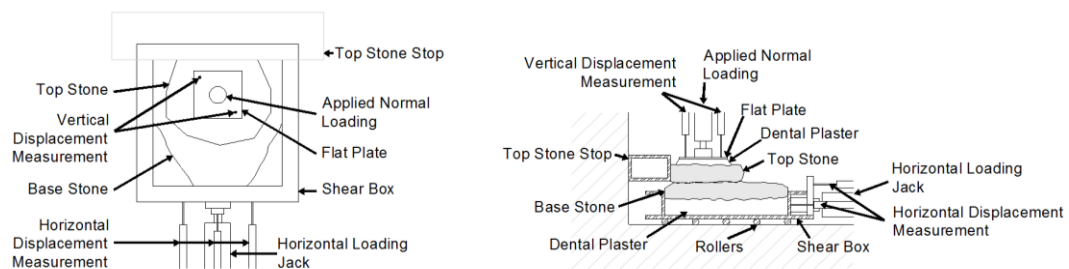


Figure 5.4: Final Shear Test Experimental setup

In each test the normal and horizontal loads were recorded directly from the load cells. Vertical displacements were measured in addition to the horizontal displacements. Each measurement was recorded at 0.2s intervals. The stone was sheared for approximately 30mm in each test at approximately 1mm/s. From these measurements the surface friction of the stone across the sheared surface was calculated for each normal loading, along with the effective stone profile and stone gradient at each data point. The stone

gradient is of interest because the horizontal force is expected to be greater if the upper stone is being pushed upwards against the normal force.

5.3.1 Laboratory Results

The tilt tests showed that the limestone blocks had a greater friction angle than the slate blocks. In all but one case the limestone showed no movement prior to complete failure (i.e. when the top stone slid completely off the bottom stone); however, the opposite was true for the slate where all but one sample showed movement 1-2° prior to complete failure, as shown in Table 5.2. This suggests that in a wall the failure mechanisms between the two stone types are likely to be differing. The limestone shows a more brittle type of failure, where the stones are less likely to move in relation to each other, and the slate walls show a more ductile failure with stones moving significantly relative to each other before failure. This supports work carried out by Mundell (2009), where his limestone wall failures showed toppling or bursting which is dominated by rotations of the stones, rather than movements relative to each other. The slate wall showed sliding at the base until gravity overtook and the wall collapsed under its own self weight.

Table 5.2: Measured Friction Angles during sliding and failure of Limestone and Morte Slate during tilt testing

Stone Type	Pair	Repeat 1		Repeat 2		Repeat 3		Average Failure Angle
		Slide Angle	Failure Angle	Slide Angle	Failure Angle	Slide Angle	Failure Angle	
Quarry Limestone	1	32	37	n/a	32	n/a	30	33
Quarry Limestone	2	n/a	43	n/a	46	n/a	47	45
Morte Slate	1	29	30	n/a	32	27	29	30
Morte Slate	2	26	27	24	28	24	31	28

Further shear testing using the shear box arrangement showed the variation in the friction as the stone moves, indicating a variation in properties as different parts of the stones' surfaces come into contact. It also reinforces the differences between different stone types and pairings as shown in the tilt tests. Friction was plotted along with the gradient of the stone movement against the horizontal displacement. Using the

recorded stone gradient an adjusted stone friction was also calculated to take this into account and shown. An example of the results produced is shown in Figure 5.5, for additional data please see Appendix 3. While eliminating the recorded stone gradient from the recorded friction shows some levelling of the stone friction angle, and hence accounts for some of the variation seen across the stone surface, it is apparent that there must be other factors affecting localised friction of the stone. It is likely that the stone roughness at a level not able to be recorded in this experiment will have an effect. Due to the makeup of limestone in particular, with particles bound in a matrix, the local frictional properties of the stone will not be uniform across a surface. In typical shear tests stones are often tested along a cut plane which eliminates the effects of local roughness.

Spikes in the gradient can also be seen across the tests, which often correspond to sudden changes in the recorded friction also. This is most likely caused by areas of the stone catching during sliding and suddenly being released once the horizontal force is great enough to overcome this.

In order to investigate the surface roughness of the stone, and if variations in the surface were present, particularly in the limestones, they were examined under an optical microscope. Figure 5.6 shows surface images of the quarry and weathered limestones taken through the optical microscope with an approximate scale. From these images it can be seen that the surface of the limestone is rougher to a scale that is unlikely to have been recorded by gradient measurements within the shear box experiments ($<1\text{mm}$) which recorded the vertical movement of the stone overall. The weathered limestone was also shown to be significantly rougher than the quarry limestone which accounts for the generally overall higher recorded friction angles (Table 5.3). Within the quarry limestone inclusions at the stone face were also seen, predominantly shell and a white crystalline material. Where these inclusions are in contact with another stone the local frictional properties will be affected.

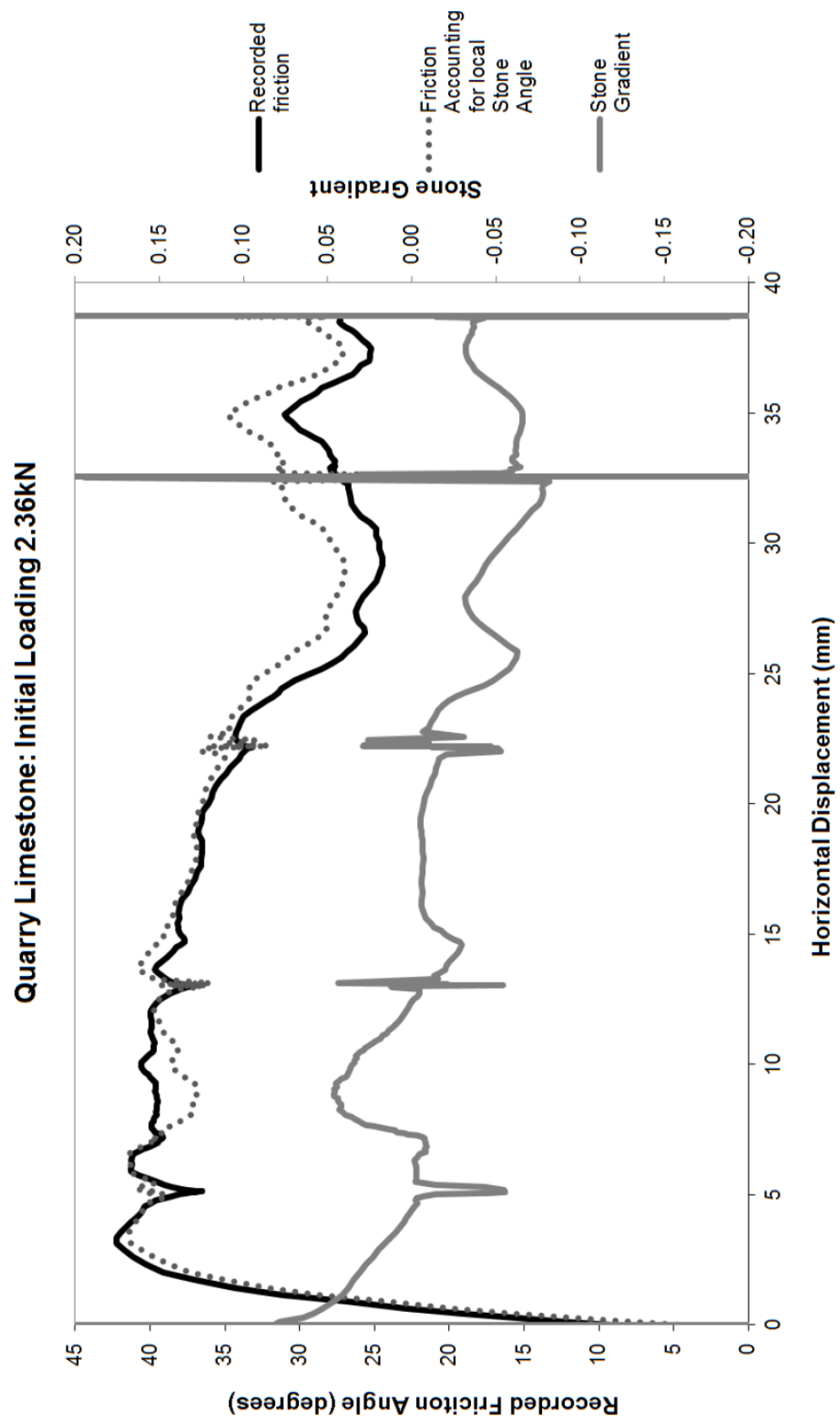


Figure 5.5: Stone friction angle and gradient of stone movement measured during shear testing of Quarry Limestone at an initial normal loading of 2.36 kN.

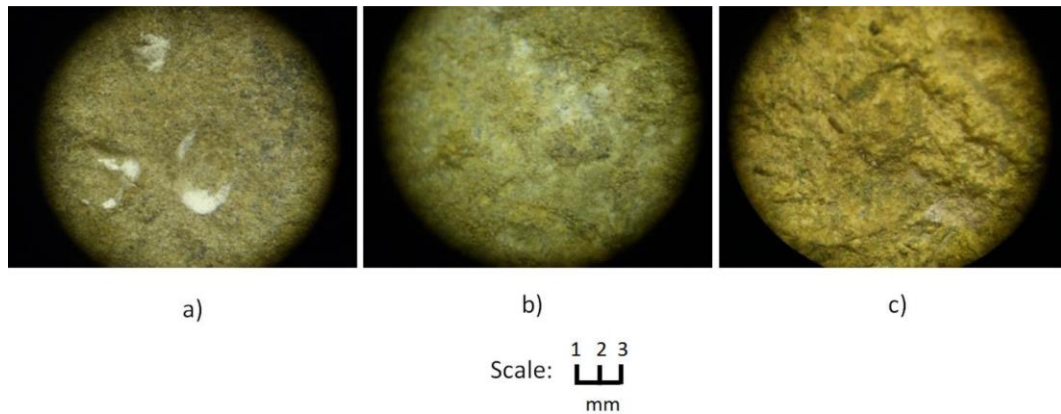


Figure 5.6: Surfaces of Limestone tested in shear under an Optical Microscope
a) Quarry Stone: Shell Inclusions b) Quarry Stone: Crystalline Inclusions c) weather Limestone: Surface Texture.

Table 5.3 shows the peak, average and minimum friction angles recorded across all the shear box tests carried out. Generally it was found that the limestones have greater frictional properties than the slate. From general literature available on stone friction properties, is to be expected. The weathered limestone was also found to have greater average frictional properties than the quarry stone; this may be partly down to the increased roughness of the weathered stone when the surfaces were compared under a microscope. These greater frictional properties are what allows the regional construction within the Cotswolds with the stone facing out of the wall, which is investigated further below. However, the range of frictions seen for the limestones was far greater than seen for the slate, approximately 20o for the limestone and 10o for the slate. This means that when making assumptions regarding the frictional properties of stones within walls there is a greater margin of error, even if average values are taken, which is likely to greatly affect the loading capabilities of the wall.

It was also seen in repeat experiments using the same stones that the average friction angle of the stone reduced as stones became worn and smooth under shearing. This has implications where stones are reused within walls and may be subject to deformations prior to reconstruction, as the general wall capacity could be reduced over multiple reconstructions.

Table 5.3: Mean Friction Values Across all Shear Tests Carried Out

	Quarry Limestone	Weathered Limestone	Morte Slate
Average Maximum friction angle across all tests	39.9	46.1	32.9
Average friction angle across all recorded values	31.3	37.1	29.3
Average Minimum friction angle across all tests	19.6	22.9	22.8
Average Range across all tests	18.4	23.3	10.1
Average Standard Deviation across all tests	5.0	5.2	2.2

NOTE: Recorded friction angles used to calculate average values taken after linear increase in friction angle had occurred at the start of each test (typically 1-2mm horizontal movement)

5.4 Field Study

A number of walls, commonly known as Cotswold Walls, were examined in the Cotswolds, Mendips and the eastern edge of Exmoor (Table 5.4 and Figure 3.1 in Chapter 3). The geology of this area includes limestones, sandstones and siltstones, as well as many strata of limited extent including Morte Slate. The British Geological Survey provides detailed online geological maps for throughout the UK, and Prudden (2002) provides information on the local geology of Somerset. The majority of the examined walls were constructed from limestone, with a small number built from Morte Slate on the edge of Exmoor. Some walls were built very recently, while others appeared to be very old.

Table 5.4: Locations of the wall study sites

Wall Location	Northleach	Sherston	Batheaston	Norton St Philip	Hestercombe
Stone Type	Limestone	Limestone	Limestone	Limestone	Slate
Stone Angles	Out of wall	Out of wall	Out of wall	Out of Wall	Into Wall
Old/New	Old with new section	Old	New	Old	Old

A number of detailed measurements were taken at each wall site, along with general observations on condition and weathering, stone type, vegetation and any other interesting features that may have been significant. Measurements of the wall included

the retained height and the total height of the wall, the wall orientation and the wall batter. Individual elements were measured within a sample area of 1m^2 . Figure 5.7 shows general setup at wall face. Within this area the angle of greatest dip and the direction of dip were measured for each stone, using a compass-clinometer. As the compass clinometer was unable to be placed directly onto the stone surface, a ruler or similar was placed flush with the stone surface within the wall and allowed to project from the wall face; the clinometer was then placed on the ruler and the stone angle recorded (Figure 5.8).



Figure 5.7: General arrangement at wall face showing 1m^2 sample area marked out



Figure 5.8: Using a compass clinometer to record stone angles in wall

The downward normal of each stone was then plotted as a point onto a hemispherical projection, along with the direction and slope of the wall face which appears as a curved line; this then shows the relationship between stone orientations and overall geometry (Figure 5.9 – for full set see Appendix 3). This provides a general and typical built envelope for each wall, allowing comparisons between styles, stone shapes and sizes, and subtle differences between wallers constructing in the same area. The stone angles within the wall could also then be compared to the recorded friction angles. It is widely given that the effective friction angle of a saw cut surface is given by the angle of friction of the surface plus the angle of the discontinuity. Using this theory, where stones within a wall that are sloping into or away from the face they will have a greater or lesser effective angle of friction, hence increasing or decreasing the ability of an individual stone to resist loading. Where this occurs over a significant area of the wall, particularly where stones slope away from the face at near the angle of friction (hence the effective angle tends to 0°), it is likely that the capacity of the wall will be severely affected.

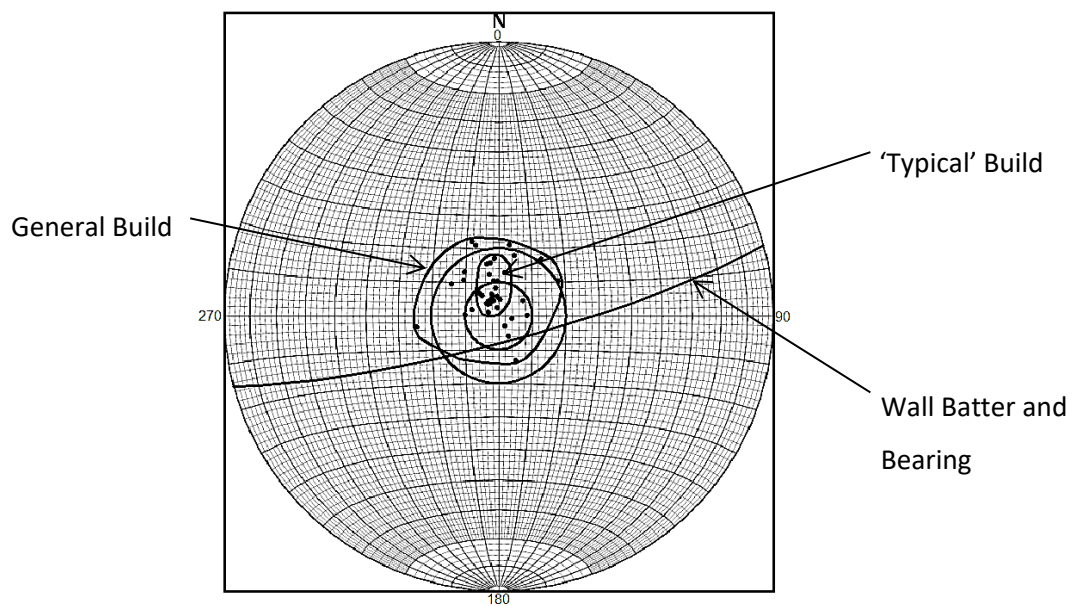


Figure 5.9: Hemispherical Projection Showing Normal Stone angles within the Wall at Northleach

Counting the number of stones within the surveyed area gave an indication of the average stone face size for the wall. Using a reflector-less total station a full height wall profile was taken passing through the surveyed section. Measurements at the top, middle and bottom of each stone gave a detailed profile of the wall, and the influence of wall distortions on the stone orientation.

5.4.1 Field Study Results

From the field study a wide range of wall envelopes were recorded showing subtleties within the generally recognised style of 'Cotswold Walls'. The hemispherical projection (Figure 5.9) shows that the stones within the wall slope towards the face, which was typical for all the limestone and sandstone walls surveyed. The stones shown in this projection within the typical envelope are generally angled approximately 10° to the horizontal and 20° to the wall face. The general envelope can be far more extensive, with stones sloping severely toward the face or back into the wall. From the observed walls it was not possible to assess the age of the wall or the extent of weathering based purely on the profile, suggesting that this does not have a significant effect on the overall wall envelope.

The slate wall showed that the stones were placed sloping back into the wall. This wall also showed far greater movement than even the most weathered limestone wall. All of

the walls showed some degree of distortion, with a typical bulged shape that is normally expected with these types of walls. All of the walls were also constructed in a horizontally coursed fashion using blocky to rectangular stones. The typical stone sizes recorded at the face of the wall, were between 0.01m^2 and 0.02m^2 .

Of the walls surveyed there were two with features of particular note. The first in Northleach, Gloucestershire showed the most extreme surface weathering of any of the walls. The weathering found around the contacts near the face of the wall had caused the stone to erode around the contacts leaving pillar type structures with fine sandy material around them (Figure 5.10a). Though these pillars may ultimately fail and cause the wall to collapse, the actual contact itself appears to have become fused through deposition of minerals, potentially increasing the strength of the individual contacts but affecting the intrinsic ductility (McCombie et al. 2012). This deposition and fusing was also seen along some of the close joints in the wall (Figure 5.10b). There were very few signs of movement under these conditions, though the adjacent section was in the process of being rebuilt following collapse. This fusing implies that the wall has been stable for a significant period of time to allow the fusing to occur.



a) Weathering around Contact



b) Fusing of Joint

Figure 5.10: Weathering of Limestone Contacts, Northleach

5.5 Discussion

The main limitation of the work reported, and the use of hemispherical projections, is that while information about stone type and orientation is obtained for the stones in the face of the wall, the construction of the core or rear of the wall is not measured. This

limits the assessment of drystone wall stability and integrity. However, failure of the front face often leads directly to failure of the rest of the wall, so any technique or methodology that improves observation and understanding of the front face is useful for assessment of the wall as a whole. If a wall is quite narrow, much of the vertical load and the shear load will be carried by the stones at the face, as the line of thrust gets closer to the front face in the lower parts of the wall (McCombie et al. 2012).

The friction testing (Table 5.3) showed that slate has a substantially lower angle of friction than limestone. This is likely to explain why the stones in the slate wall were tilted back into the wall rather than toward the face, because sliding cannot occur without pushing the mass of the wall up these sloping surfaces, allowing the wall to resist greater forces. If constructed with the stones sloping outwards as seen in the limestone walls, the ability of the walls to support earth pressure would be considerably reduced, and a great thickness of construction would be required to maintain overall stability. It may be argued that all walls should be constructed with the stones sloping back into the wall to increase resistance to sliding, but limestone is constructed with outward sloping stones to reduce the amount of water penetrating the wall and causing stone degradation, which could also be detrimental to the wall. The friction testing results show that the limestone has a large enough shearing capacity to allow for this tilting.

The shear testing and field observations also suggest that weathering may not be as detrimental to the walls as is usually assumed. The friction angles observed during shearing of weathered limestone, although over a larger range, were generally greater than for the quarry limestone, suggesting there will be a greater interaction between the stones within the wall and hence a greater resistance to any destabilising forces. In the field, fusing of joints and contacts was observed which may strengthen the contacts between the individual stones. However this fusing will also make the wall more brittle, causing a loss of strength during small movement. The frictional resistance between the individual stones will persist at large displacements, allowing a ductile wall failure.

However the weathering of the stone results in a progressive loss of mass, and a reduction in the strength of individual stones. It may also reduce the permeability of the wall, through deposition of weathered material and trapping of sediment, making it more vulnerable to rising pore pressures within the retained earth which could lead to

wall failure. The age of some of the current walling stock has shown that this weathering may take many years.

The severe angles found a minority of stones in the other walls, are approaching the average friction angles recorded in the shear testing, indicating that the stones are only just able to support their self-weight, and have little capacity to carry shearing loads from earth pressures. This potentially makes them more prone to sliding. Where only isolated stones slope steeply outwards, redistribution of loading will occur together with minor local deformations, and provided that adjacent parts of the wall have the capacity then the wall as a whole will remain stable. This ductility allows local imperfections to be tolerated.

5.6 Conclusions

This study highlights the variations in walling that can be found in a distinct geographical walling area; these variations are important for the bodies who take ownership of these walls for assessment, as these slight variations need to be considered, unlike for regular mortared masonry.

Particularly within the Cotswold area, when assessment is carried out the slope of the stone may also need to be considered - particularly where movements have occurred, as this may have accentuated the original slope to an extent which may be detrimental to the wall itself. This has been shown to be easily taken and recorded using easily available equipment, and can be targeted to areas of interest if required. To do a whole wall would be unfeasible due to the time taken, however by taking samples of areas of the wall face a picture of the overall construction can be made.

The field study also indicated other visual aids that may contribute to the assessment of a wall's stability. For example, in stones such as limestone that are prone to weathering, deposition of materials was seen around joints, causing fusing in some cases. For this to occur the wall must be in a stable state with little movement otherwise, cracking would be seen in these areas. However, the weathering of the stone over time ultimately poses its own risks to the stability of the wall, by removing material which ultimately will make the face unstable. If continued assessment of these walls is carried out this effect can be

monitored, and suitable measures put into place prior to it becoming detrimental to the wall's stability.

The friction tests highlighted the variability of surface friction across the interface between two uncut stones, and between differing pairs of stone of the same type. If numerical methods relying on stone properties are to be used this should be considered, and analysis carried out with an upper and lower bound of frictional properties, as this is one of the main contributing factors in drystone stability analysis. Also if, as in typical Cotswold constructions, stones are sloping out of the wall, then the range of values for this slope should be taken into account when considering the effective friction angle of the stone.

Chapter 6

Geophysical Investigation

6.1 Introduction

Geophysical techniques have previously been used to assess a wide range of retaining and historic masonry structures which are discussed below. This chapter reports investigations to determine whether using such techniques could reveal information about the wall structure, such as its width, the presence of large stones, or any significant voids within the wall.

Electrical resistivity surveys measure voltage drops over defined distances as a known current is passed through a region of soil. In the modern form of Electrical Resistance Tomography, a linear array of many electrodes is used in many configurations to allow a calculation of a two-dimensional resistivity profile. As the electrical resistivity is determined by the type of ground, its degree of saturation, and the nature of the soil and its pore fluid, conclusions may be drawn about the profile of the ground conditions. However, all work with this technique treats the ground as a continuum. In a drystone retaining wall, the stones are connected only at discrete points, and the path the current would take becomes very unclear; also, obtaining a good connection between electrodes and stones would often be difficult. It was therefore concluded that this technique was not worth investigating further.

Seismic investigation depends upon measuring the time it takes for shock waves or sound waves to travel through a section of ground. Very short pulses at high frequencies can be used to carry out shallow investigations, or longer wavelengths and

lower frequencies for deeper investigations. This technique faces similar problems to electrical resistivity surveys in drystone structures: connecting to the structure, and the complex paths the signal might follow, leading to results which would be very difficult to interpret. In seismic investigation, there would also be the potential hazard of sending shock waves through a potentially unstable structure. Therefore this method too was discounted.

Ground Penetrating Radar (GPR) sends pulses of electromagnetic radiation through the ground, and detects the return of reflected waves. Because the signal can pass through voids as well as solid ground, it is much more suited to drystone structures than the methods described above. It is non-destructive, and does not even threaten the stability of a structure. The signal is reflected back where there is a change in material or density creating an interface within the area being scanned, this reflected signal is then picked up and recorded by the GPR machine from which a visual image can be created. Within the visual image arcs are formed at the interfaces which can then be interpreted accordingly. With further processing an image can be formed showing features within the scanned area. GPR devices are available using a range of signal frequencies, with some using more than one frequency to scan. In general the lower the frequency the greater the penetration depth but with less resolution and the higher the frequency the lower the penetration depth but with a higher resolution.

Typically GPR is used for ground investigations. This work was carried out in conjunction with Dr S.R. Pennock and Dr C.H.J. Jenks from the University of Bath, who are involved in research investigating the use of GPR to find buried utilities (Pennock and Jenks, 2014). They operated the equipment and processed the data, providing the visual images shown.

6.2 Literature review

There has been various work into the non-destructive testing of retaining walls, both for the purposes of assessment, and after visible damage has occurred in an attempt to diagnose the cause of failure. Much of the assessment work however is concerning the locating of reinforcement bars in concrete retaining walls such as the work by Hugenschmidt and Kalogeropoulos (2009). However a few studies have been carried out on drystone retaining walls, and on walls with some similar characteristics.

One of the larger studies carried out was by Kavanagh et al. (1999) on the use of ground penetrating radar (GPR) to investigate masonry retaining walls. As part of the study six different walls were investigated using GPR, in order to assess the validity of it as a form of investigation. All of the walls investigated were either drystone or are likely to have been originally built as drystone. The frequencies used during the investigation ranged from 250-900MHz, the lower frequencies giving greater depth of penetration but the higher frequencies giving better resolution. By using them in combination it is possible to get the best possible information. Kavanagh et al. took both horizontal scans along the wall faces, as well as vertical scans at locations of their choice.

It was determined by Kavanagh et al. that there were generally three distinct areas within the GPR results, the first area showing the face and likely reflections from interface from the facing material and the air, and then the fill behind; they then identified an area with a lot of disturbance which they attributed to an area of coarse fill with voids; and onto a more uniform area of the image which correlated to a more uniform material behind the wall. However in order to make a clear assessment Kavanagh et al. made use of other methods as well. Where possible 40mm holes were drilled into the walls to enable the thickness of the wall to be taken for calibration, as well as to assess the backfill and to confirm the presence of voids. They also emphasise that a good visual inspection of the wall is also needed. The GPR was also able to pick up features that are linked to areas of instability, although it was noted that the assumption cannot be made that what is stable for one wall will be stable for another. In one wall that Kavanagh et al. studied it was found that a particular formation was found to coincide with areas of stability whereas in another wall it was found to coincide with area of instability. This enforces the need for GPR to be used in conjunction with other methods, and that visual inspection is required.

Although it appears that Kavanagh et al. may have drilled drystone walls as part of the study, the drilling of an unmortared structure in order to gain information about the wall and backfill is not ideal, particularly in areas of potential instability. Overall, the paper shows the potential of using GPR as an investigate technique in conjunction with other methods.

Deidda and Ranieri (2005) used seismic tomography to help assess an embankment and retaining walls showing severe cracking down the walls and along the top of the

embankment. The purpose of the study was to provide a potential solution for the problem by verifying the initial ideas on the causes of the instability, as well as to gain the wall geometry and the internal geometries of the crack. The subsoils were also characterised along with the parameters of the underling rock. In order to carry this out, as well as the tomography, laboratory based ultrasonic measurements were carried out and borehole records kept.

The study confirmed that the issues within the wall arose from construction issues. Hence Deidda and Ranieri concluded that seismic tomography is a useful and accurate tool for providing information on the various parameters they required, and that in addition to the other laboratory methods allowed suitable solutions to be put forward.

The issues of potentially using this method on drystone retaining walls again come from the unmortered nature of the walls. It is unlikely that when drilling through drystone wall that the stones immediately around the drilling sight will be able to support themselves, and significant damage could be caused to the wall face. It is also likely that were this method to be used, as in this case, there would be signs of instability already in the wall, and the bore holing process would induce some form of vibration within the wall itself which may cause partial or total collapse. It is possible that the area around the boring sight could be mortared if deemed necessary, however grouting a drystone wall has its own issues associated with drainage and water build up, so this may also not aid the wall overall but just the immediate area.

One of the main studies carried out on drystone retaining walls is by Bishop and Koor (2000) regarding the masonry retaining walls in Hong Kong. The study was prompted by the collapse of a wall in 1994, when it was decided to investigate how non-invasive techniques may be used. A number of options were considered including ground penetrating radar and electrical imaging, alongside pre-existing ground investigation data. Bishop and Koor had six main aims from using these techniques: determine wall thickness; investigate wall composition; locate voids; identify areas of moisture; locate water utilities behind the wall; and target the ground investigation where required.

Bishop and Koor suggested that for wall thickness a more conventional method of wall probing of weep holes may be more suited, however they note that not every wall has weep holes (also if you were to use this method in the UK very few drystone walls are

built with weep holes given the naturally free draining nature of the walls), and if they do this then assumes that the weep holes penetrate the full width of the wall. It was found in some of the walls studied that the wall had two phases and that the weep holes only reflected the later phase of the wall built in front of earlier phases, also it was noted that the probed length could penetrate the soil behind. In order to supplement the probing of the wall Bishop and Koor also used drilling of the wall face however, due to the nature of the materials, recovery from this was deemed to be poor, making interpretation difficult. They also suggest that these methods only produce data for discrete points and that anomalies within the wall may be missed, leading to unexpected failures. It is from this consideration that geophysical methods are suggested.

When using the geophysical techniques Bishop and Koor suggest that an additional visual survey be carried out to locate feature which may produce apparent anomalies in either the GPR or electrical imaging results, and so prevent misinterpretation e.g. proximity to fences, steps and electrical installations, location of features attached to the wall face. In the case study carried out by Bishop and Koor it was deemed that to gain useful information from electrical imaging that further intrusive work would be required, and thus the method was not very successful. The GPR in comparison seemed to be relatively successful at indicating the wall thickness; however it is implied by the author that intrusive work was needed in order to gain velocities for data interpretation. The ground investigations carried to predominantly appear to be the use of trial pits behind the wall, along with boreholes through the wall and into the backfill. This appears to have given the authors the most amount of useful information. This information was then used to further aid the interpretation of the geophysical data, from which a section could be produced.

Overall Bishop and Koor deemed that the geophysical techniques are useful for identifying if a wall is particularly thin and identifying any anomalies within the wall or backfill. However the wall on the case study is deemed to be 1.8-2m thick, which is substantially thicker than drystone retaining walls you would expect to find in the UK, so how effective these methods would be is unknown; however, the ability to identify areas that may potentially need to be further looked at is useful.

6.2.1 Non Destructive Assessment of Masonry

The non-destructive assessment of masonry is a well-covered topic; the assessment of historical masonry dominates the literature. Historic masonry has many similarities to drystone walling in that the exact construction is often not known, and typically is of a more random fashion than more modern masonry. Historic masonry however usually included a binder, but this may have deteriorated and no longer be present in some cases. This section will look at methods that have been used to assess other forms of masonry construction, including those other than historic, and how they may be applicable to drystone.

Healy (2008) used acoustic emissions to detect damage in historical type masonry. His tests were carried out on freestanding wall panels specifically built for testing. Instead of using a traditional mortar, modern mortars were used. Each panel was initially forced to crack under vibration and further under line loading to the rear of the section. The wall was fitted with acoustic sensors and the noises produced by the wall during testing were monitored. Signs of visible damage were also recorded during testing and compared to the acoustic readings. For the vibration phase of the testing efforts were made to eliminate the noise induced by the vibrator, so that the only noises recorded were from the wall movement itself. However under analysis when these measures were removed, although the number of acoustic hits increased, their overall pattern remained unchanged.

Healy deemed that listening to the acoustic emission from the wall was a useful way of detecting damage within a wall, with potential damage correlating to the hit rate of the acoustic emissions. However it was found that the source of the emissions was not where visual damage was seen. It was proposed that this is due to the inhomogeneous nature of the wall. In one case emissions were also recorded where no visual damage could be seen, from this Healy proposed that internal wall damage may be being detected. However to detect damage Healy required sensors to be with 12 inches (approximately 300mm) of this, meaning, on a larger wall a relatively large number of sensors would be required.

Although no use of this method is proposed by Healy, it is likely that it could be useful for monitoring. It also has the potential to be applied to drystone in a permanent

monitoring situation, as if the wall starts to move then emissions would be picked up and recorded, and if there were a sudden increase in emission or continual high level then this may highlight issues within the wall. However it is likely that a drystone wall would be more inhomogeneous than the wall sections tested by Healy due to lack of mortar, so pinpointing damage may be an issue, particularly if regular visual checks are not carried out.

A number of studies have been carried out regarding historic bridges which use various methods of assessment. Lubowiecka et al. (2009) and Arias et al. (2007) used very similar methods to analyse two separate ancient bridges. Both used methods of imaging to produce models of walls, along with GPR results, to enable finite element analysis of the bridges concerned. In each case 3D analysis was carried out. The methods for construction of the model used by the different authors varied with Arias et al. using photogrammetric methods and Lubowiecka et al. using laser scanning. Arias et al. also appear to have made a far more detailed model, in which every stone was outlined, to produce a wire model. By doing this cracks within the structure could also be seen and allowed for in the analysis. With the photogrammetric methods however some issues were found with access in order to be able to take the images needed to produce the model. However in both cases the models produced were deemed to be satisfactory for the studies.

Either of the methods used to produce the bridge models may be suitable for the monitoring of drystone retaining walls and potentially producing models that could be analysed, however only face detail could be obtained as the rear of the structure by its nature is inaccessible. Also the approach used by Arias et al. producing a wire frame model would allow for the movement of individual wall elements to be seen over time, by comparison to previous models, and highlight areas of concern.

Lubowiecka et al. and Arias et al. both use GPR as part of their surveys. This appears to be a popular technique when trying to assess many forms of masonry (Solla et al. 2010, Maierhofer and Leopold 2001, Binda et al. 1998, Flint et al. 1999). In the Lubowiecka and Arias studies the GPR was used to assess the properties of the fill, as well as gain an idea of the barrel thickness, for use in the finite element models. In both cases the GPR produced sufficient results to enable the fill material to be determined, as well as

defining the geometry of the bridge arches, and the water levels below the bridge, which were used in the models produced.

Another study that used GPR to help assess historical masonry bridges was carried out by Solla et al. (2012). In their study they found that the GPR was able to identify various features within the bridge such as areas of restoration, as well as identifying areas of different fill types and potential voids. As with the previous two studies the GPR also showed the arch within the bridge and the water level below. However Solla et al. found that the GPR was unable to highlight any cracking within the structure, or areas of moisture. In terms of data interpretation Solla et al. also note the need to be able to filter data to reduce noise within the results and improve interpretation, as well as the need to know exact dimensions to enable material velocities to be estimated and aid data processing.

Another method of assessment suggested for the assessment of bridges is suggested by Shigeishi et al. (2001) which is acoustic emissions. In their study Shigeishi et al. studied both a modern reinforced concrete, and a historical section of bridge. During the study acoustic signals were transmitted into the structure and the emissions recorded. In the study it was found that this method is useful for detecting the propagation of cracks and for the condition assessment of bridges. However it was found by Shigeishi et al. that in the historical masonry bridge section the emissions recorded were at lower energy than in the concrete section. It was also found that visible cracks did not emit much energy, which if this were to be used on a drystone wall may be a major issue as it could be that each joint in the wall, given their un-mortared nature, acts in a similar manner to a large crack. They also found issues with attaching sensors to the rougher surfaces of the historic masonry, which would also be present with drystone walls.

6.2.3 Ground Penetrating Radar (GPR) – Daniels (2007)

Ground penetrating radar is used for a wide range of applications from planetary exploration to detection of buried mines. The majority of GPR devices work by sending out a signal from a transmitter, a receiver then picks up back scatter from the target in question which is then processed before a visual image is produced.

The range GPR is predominantly governed by the total path loss. Daniels provides a simplified example of how this can be calculated for a particular distance. However the

three main contributors to this loss are: material losses, spreading losses, and scattering losses. Material losses are those from the material the signal is travelling through. From the information provided by Daniels it appears the greatest material losses are in wet soils; for example moist clay losses are around 5-300dB m⁻¹, compared to 0.01-2dB m⁻¹ in dry sand. Spreading losses are due to the spreading of the signal in all directions, and are generally indirectly proportional to the distance of the object to the power of four. Scattering losses are caused by the boundaries between layers, and are said to be typically in the order of 1.6dB for the interface between the 1st and 2nd layers.

GPR is also affected by clutter i.e. signals that do not relate to the target, but occur within the same time window and have similar characteristics to those of the target. Clutter has a number of causes including breakthrough between the antenna, and multiple reflections between the ground and antenna. This can be filtered out at the processing stage.

In terms of drystone walling there is potential for GPR to identify features, it is likely that lower frequency radar will be able to identify features behind the wall, and higher frequencies will be able to identify features within the wall itself. The main issue with this technique on drystone is likely to be the many air stone boundaries within the wall, which will potentially create a lot of noise/clutter which will need to be processed out. Also the roughness of the surface may produce issues in using the equipment as well as in the interpretation of the results.

6.2.3 Geophysical Technique Summary

There are many potential geophysical techniques that have previously been used and proven on historic masonries including seismic, electrical resistivity and acoustic techniques. Each of these has the potential to indicate various attributes of a wall, however these techniques required either the input of vibration signals into the wall, or probes to be inserted and potentially grouted into the wall face.

It was deemed that with a potentially unstable drystone wall the input of vibrations may be detrimental to its stability; also the grouting of areas of the wall face, even in isolated areas, to allow the insertion of probes is not ideal, and if large areas are grouted it could potentially prevent the free drainage of water through the wall resulting in increased backfill pressures.

By using GPR the need to input vibrations into the wall is mitigated and it can be used at the wall face without the need to insert probes into the wall face. Within the University of Bath research is being carried out into GPR, and the researchers involved were willing to contribute their provide knowledge and expertise to this potential application.

6.3 The Study

The GPR work was carried out in conjunction with members of the electrical engineering team who have access to the equipment required, as well as the knowledge to help interpret the data recorded.

Reading were taken using a commercially available GPR unit which produced signals at 250 MHz and 700 MHz, and is typically used for ground applications such as finding pipes; this is considered to be of relatively low frequency. Readings were taken both along the wall face and on the ground behind the wall. As the wall was relatively low in height (about 1m), two readings were taken at the wall face, one with the wheel of the GPR unit along the top course of stone and one with the wheel of the unit running along the bottom course of stone. Behind the wall three readings were taken, immediately behind the wall, 0.5m back and 1m back from the wall. Each reading was repeated three times from left to right of the wall.

In order to take the readings along the face of the wall the GPR unit was lifted and rotated through 90o and held against the face of the wall as shown in Figure 6.1.

It was thought that certain features may be picked up by the GPR including:

- The back of the wall
- Any voiding within or behind the wall
- Where through stones are situated within the wall
- Information regarding the backfill that may indicate as to the nature of the material being retained



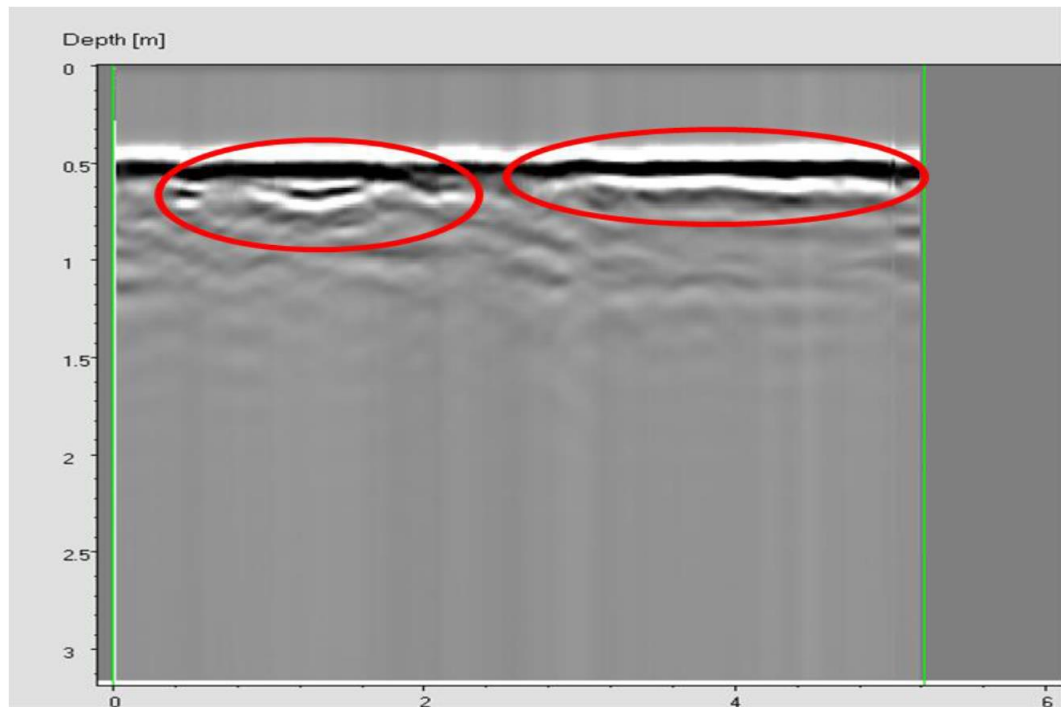
Figure 6.1: Using the GPR antenna to take readings of the wall.

The wall scanned was chosen as it was due for demolition, so any features identified using the GPR could be uncovered and explored to see if they had any relevance to the structure. The wall itself was around 1m in height and constructed using limestone uncovered on the site during previous construction works, and had been erected for approximately 3 years. It was also known that behind the lower levels of the wall was the natural bedrock, and that the upper level of the wall retained fill material. By taking readings over both the lower and upper half of the wall it was hoped some differences would be seen between them.

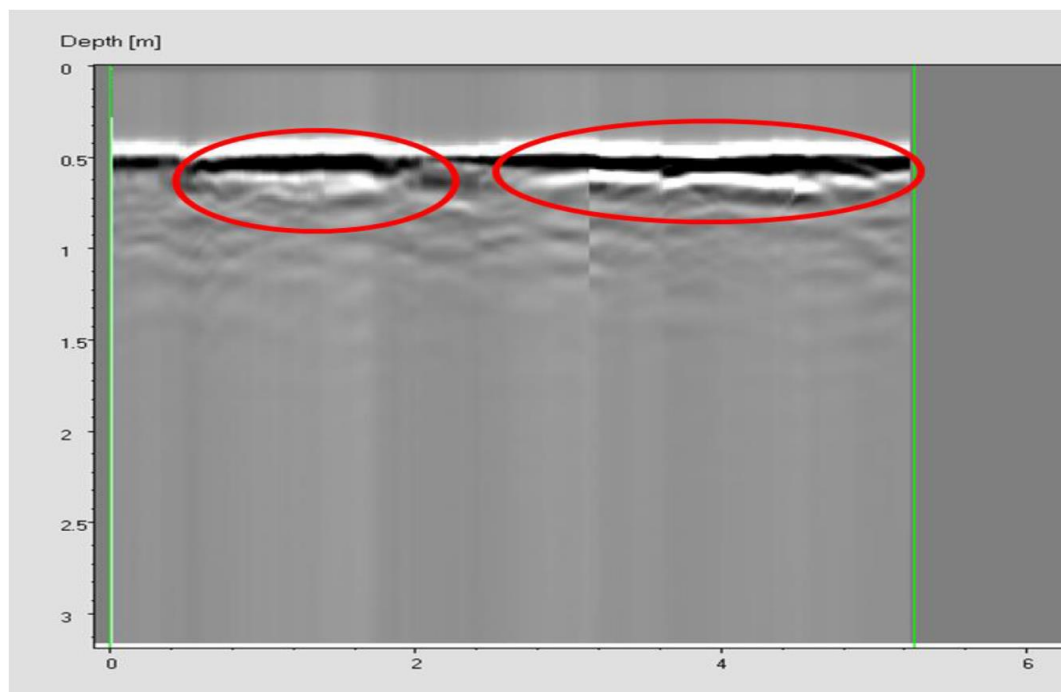
Scans were taken at both frequencies before being formatted by the electrical engineers into a visual representation which could then be analysed to identify any features of interest which could then be looked at during demolition.

6.3.1 Results

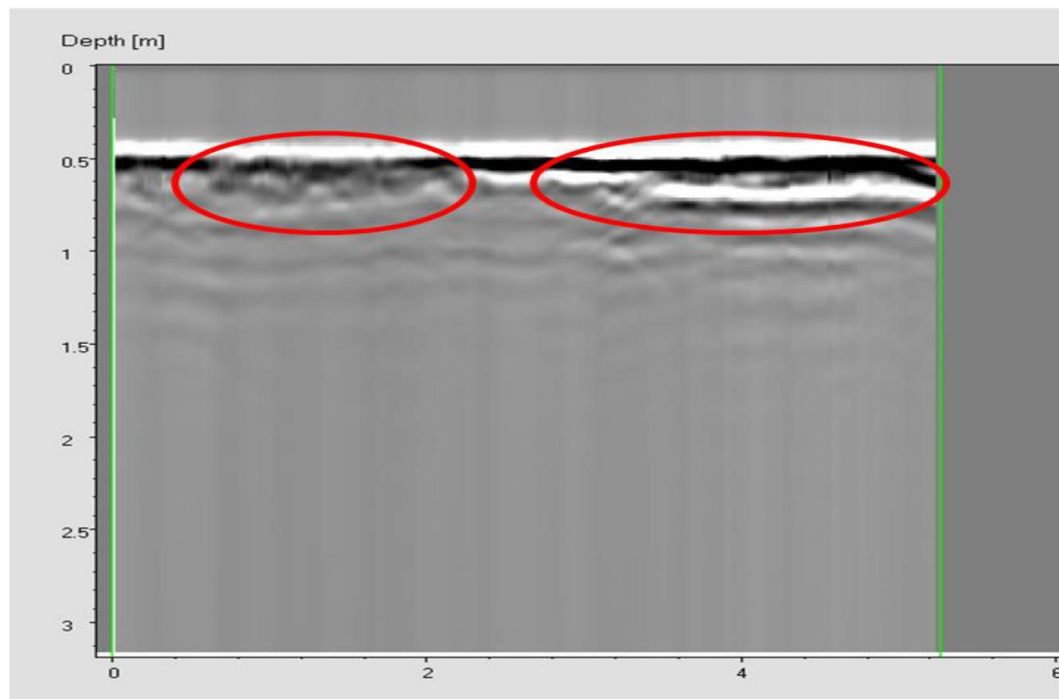
From the images taken 2 main areas of interest could be seen, predominately from the scans taken on the level backfill behind the wall (Figure 6.2). The scans at the wall face did not appear to show any prominent features (Figure 6.3).



a) Immediately behind the wall



b) 0.5m behind wall



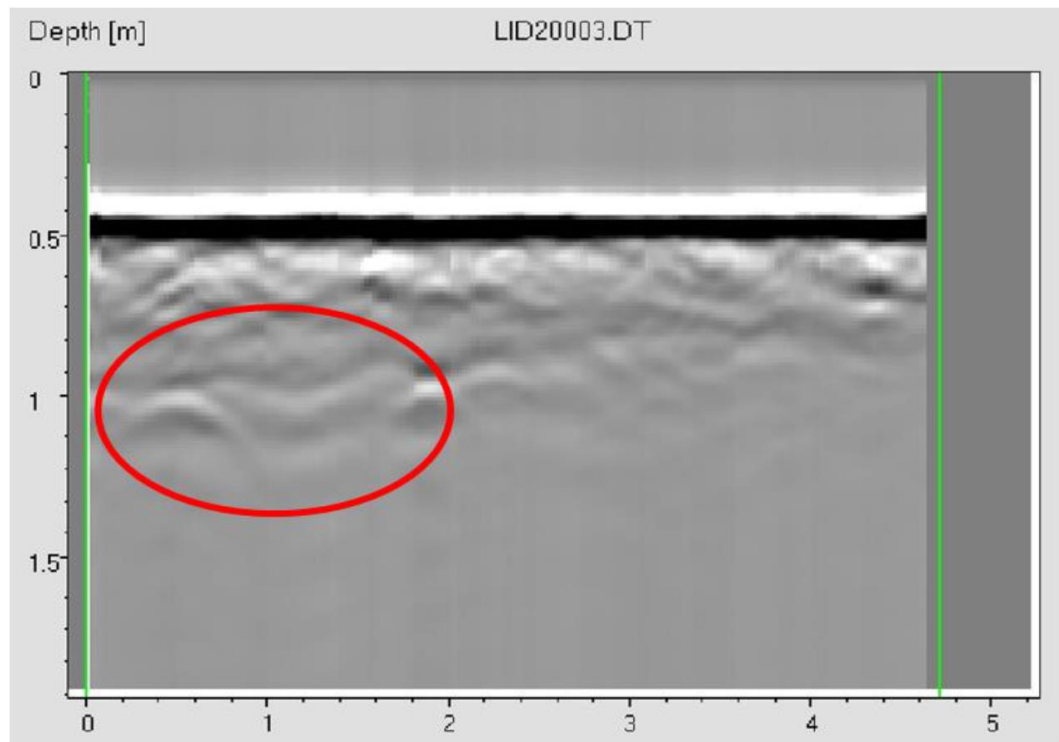
c) 1m behind wall

Figure 6.2: Areas of interest shown up using GPR: a) Immediately behind the wall;
b) 0.5m behind wall; c) 1m behind wall

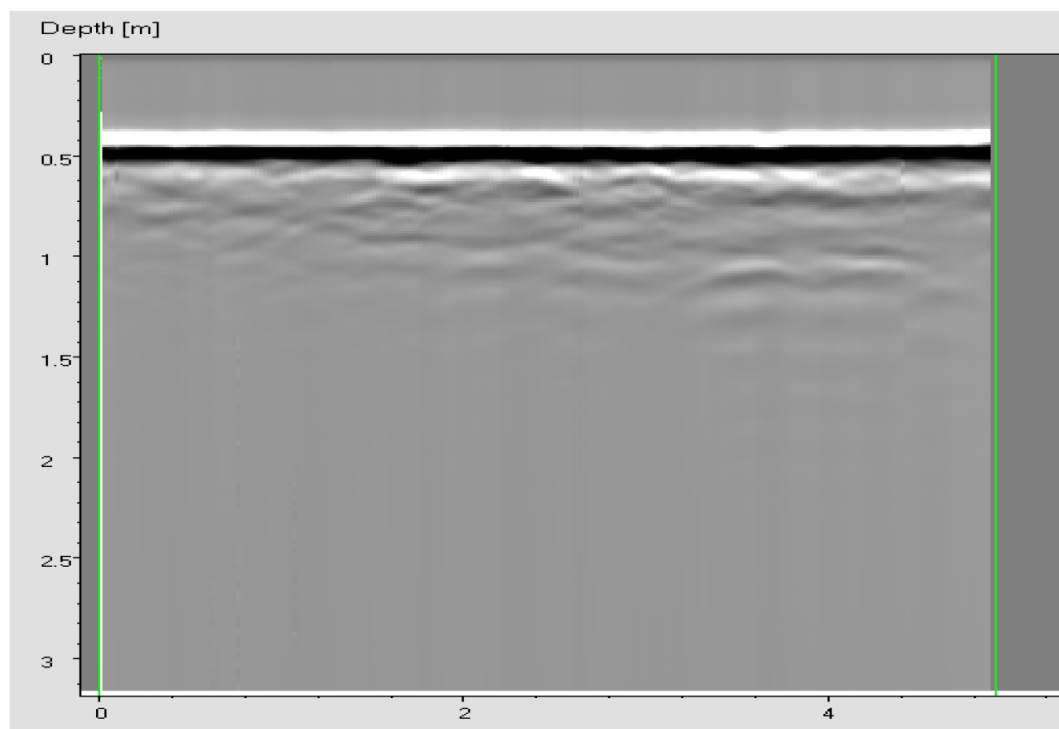
It was found that each pass with the GPR gave very similar outputs, as can be seen in Appendix 4. This proved the consistency of the method although very few features appeared to be picked up by the technique in this instance.

During demolition of the wall the potential features that were picked up could be investigated to see if any potential cause could be seen.

The feature to the right seen in the scans behind the wall appeared to coincide with an area of fill that differed from the typical backfill around it. This area of fill was visually darker than that around it and was relatively stony. It also potentially had a higher moisture content than that around it and could easily be moulded (Figure 6.4).



a) Top of wall



b) Bottom of wall

Figure 6.3: Scans along top and bottom of wall. Top scan shows an area of interest approximately 1m along wall corresponding to that seen in scans along rear of wall. Bottom scan appears to show relatively little information.

Upon investigation the feature to the left seen in scans behind the wall and in the scan to the top of the wall face could be seen to be associated with a significantly large stone, approx. 1m² in plan, within the top layer of the wall (Figure 6.5). When removed the backfill below this stone appeared to be loosely compacted top soil, with very few stones within it. Due to the loosely compacted nature of this backfill there was also the possibility of voiding in this area.

Due to the lower frequencies it was not expected that features within the wall itself would be picked up using this technique. However it was hoped that the rear of the wall may be seen, however the results produced proved to be inconclusive; this may have been because the wall was relatively low and slender for the frequencies used.

Issues were also found in keeping the antenna in contact with the wall due to its large size, which may have had an effect on the results. It may also be that the results were affected by the inhomogeneous nature of drystone, causing the signals to be disrupted by the multiple stone-air boundaries within a wall.



Figure 6.4: Fill Excavated in area of interest to right of wall. Though not immediately obvious in image, this area appeared darker than that around it with a higher stone and moisture content.



a) Stone in situ in wall



b) Backfill under stone when removed, showing loosely compacted top soil

Figure 6.5: Significantly large stone within wall corresponding to feature to left of GPR images.

6.4 Conclusions

Although some features appear to have been identified by GPR, particularly when used behind the wall, overall, the use of GPR to determine wall features in this case proved to be inconclusive. It has been proven through previous works that it is of use in historic masonry, and due to the similarities it was hoped that it would help identify features within the wall. It is likely that issues arose for a number of reasons, including the relatively low frequency of the equipment available and the multiple stone air interfaces, due to the inhomogeneous nature of the wall, causing noise in the readings. Also, historic masonry, or any other types of masonry, is more planar and has a smoother surface both at the front face, where the GPR is in contact, and at the back of the wall, which would show as a flat contact between the masonry and the soil.

It is possible a smaller higher frequency unit may provide more conclusive results and would warrant further investigation. Higher frequency units are available as hand held units which would be easier to use at the wall face, and to keep a constant contact. Higher frequency devices also have a lower signal penetration depth, therefore there is a greater potential to gain information about the wall construction itself. Testing of alternate frequencies would also allow the effects of the inhomogeneous nature on GPR results to be further investigated.

Chapter 7

Thermal Imaging

7.1 Introduction

Thermal imaging, otherwise known as infrared imaging, uses a specialised camera or device to detect the infrared radiation emitted from an object, which varies according to its temperature. This is then processed by the camera to produce a visual image from which the temperature of the objects surface can be taken. Temperatures are denoted visually by either a colour or grey scale between defined maximum and minimum temperatures, the difference between which can be as small as a few degrees.

Originally used to enable vision in poor visibility or the dark, thermal imaging is now used in a wide range of applications from medical and veterinary uses through to industrial applications. In terms of drystone retaining walls thermal imaging allows the surface temperatures of the individual stones to be seen, revealing any areas that are of a different temperature to the surrounding wall, indicating a feature within the wall.

Within the construction industry thermal imaging is currently most commonly used for building physics purposes, to study building heat losses, and to identify areas of improvement in obtaining energy efficient homes. Within civil engineering thermal imaging has had little exposure, despite being widely used in other area of engineering such as in the assessment of aircraft structures. However in aiding the assessment of drystone walling it is a potentially useful tool because these structures are constructed using individual elements that are not bonded, and so have a limited thermal influence on each other.

Thermal imaging has many advantages as a potential assessment method. It is quick and easy to use, with the camera equipment being very similar to a conventional digital camera. Adapters are now also available to attach to smart phones to enable them to be used as a thermal imaging devices. Images can then easily be transferred to a computer for analysis, using software often provided with the camera. These analysis programs enable the visual scale to be changed to a number of different colour schemes or greyscale to suit the user, as well as allowing the user to narrow the range of temperatures displayed, typically to within 2°C, allowing even small changes in temperature to be visible. It is also possible to take more accurate measurements of points within the image or over an area if further analysis is required. The software is simple to use and results can easily be obtained with little to no additional training. Conventional images of a wall are typically taken during wall assessments. Many thermal imaging cameras also have the capacity to produce a conventional image alongside the thermal image, meaning the use of this technique is unlikely to significantly lengthen the time taken on site, while adding useful additional information. The visual images taken by the camera are also useful for comparison to the thermal image in identifying features. The amount of kit needed is also not significantly increased, if at all.

The use of thermal imaging for assessing a drystone retaining wall is based on the differing sizes of the stones within it and their contact to the backfill. It was anticipated that due to the differences in temperatures caused by these variations, thermal imaging would enable the identification of features within the wall such as through stones, and areas that may be of concern and warrant further investigation. For example a through stone is larger in size than those around it penetrating further into the wall, ideally being in contact with the backfill while still being visible at the face. Its larger size gives it a greater thermal capacity than the other stones, and its constant contact with the backfill, which stays at comparatively constant temperature to the air, mean that it is likely to change temperature more slowly than the stones around it; thus when it is viewed using thermal imaging it will appear either hotter or cooler than the stones around it, depending on the time of day and the seasonal temperatures. Similarly an area that has come away from the backfill will show warmer or cooler than the general temperature of the wall, but over an area rather than an individual stone. Similar effects may also be seen where there is water build up.

Thermal imaging is not expected to provide a definitive answer to the stability of a wall, but rather to aid the engineer in their judgement and identify the location of defects within the wall. The prime factor when considering thermal imaging is not the actual temperature, but the temperature differences seen across a wall, section of wall or between stones. Seasonal and daily temperature changes will cause different temperature patterns within wall constructions, as will daily variations in incident radiation, which are also dependent on wall orientation.

An initial trial was carried out on a new section of limestone wall in Northleach, Gloucestershire, where the wall construction is known to be good and has obvious through stones. Images were also taken of other areas of this wall, which shows a wide variety of historic construction within it. Following this initial trial, imaging was undertaken on other construction and stone types in France and Wales to test the validity of this method in providing information across a wide range of wall constructions. Following the field investigations, simulations were carried out using WUFI, a 1D thermal simulation program commonly used in building physics, to validate and extend the field findings.

The aim of this study was to establish the validity of this technique as an assessment tool, as well as to provide the basis of guidelines for the use of this technique should it be successful.

7.2 Literature Review

Thermal imaging works on the basis that all bodies above absolute zero (-273.15°C) emit infra-red radiation, which lies between visible light and microwaves on the electromagnetic spectrum (Flir, 2011). This is typically felt as heat, however using specialist cameras this infra-red radiation can be detected and turned into a visual image. The warmer an area the greater the amount of infra-red radiation that is emitted.

The emissivity of an object also needs to be considered when using thermal imaging, as differing materials having differing emissivity's within one image can make it appear as if the materials are at differing temperatures even though in reality they are very similar. The emissivity's of some of the common walling materials are shown in table 7.1.

Table 7.1: Typical Emissivity values (Omega, n.d.)

Material	Emissivity Co-efficient ϵ
Granite	0.45
Limestone	0.95
Sandstone	0.67
Slate	0.67-0.8

If the emissivity of the object to be imaged is known it is also usually possible to set this within the camera, which will then provide accurate temperature readings. However in a drystone wall it is typical for the wall to be constructed from one material where it can be assumed the individual stones have similar emissivities, and as this study is interested predominately in the temperature differences and not the actual temperatures this value is unlikely to be of importance. However where a wall is made from more than one material it is likely that visual inspection will highlight this, and allowances can be made in the assessment of the thermal image.

In order to identify through stones in particular, which are generally larger than its surrounding stones, the principles of specific heat capacity and heat transfer need to be considered. Specific heat capacity is the amount of energy required to change the temperature of 1kg of mass by 1°C. Some typical values are shown below.

Table 7.2: Specific Heat Capacities of typical wall construction materials (Engineeringtoolbox n.d.)

Material	Specific Heat Capacity kJ/kg.K
Granite	0.79
Limestone	0.91
Sandstone	0.92
Slate	0.76
Water	4.18

For the same amount of given energy, either heating or cooling, the temperature change in a stone with greater mass will be less than for a stone with a smaller mass. This is further aided by the likelihood of through stones being in constant contact with the backfill which remains at a fairly steady temperature throughout the year. Where existing stock has been in situ for a number of years the through stones are likely to adopt a temperature nearer to that of the backfill, unlike the smaller stones which will

be more directly affected by the air temperature, since they are not in direct contact with the backfill. However some thermal transfer through the wall layers will still occur.

This prolonged thermal transfer from the backfill should also mean that any voiding behind the wall should also be visible. Indications of water behind the wall should also be able to be detected, either directly by altering the heat transfer properties and temperature of the backfill, or indirectly by water on the front of the wall causing localised cooling of the face through evaporation.

7.2.1 Previous Structural Studies

Thermal imaging has successfully been used to identify defects in both concrete bridge structures (Clarke et al., 2003) and in airport pavements (Moropoulou et al., 2001). The use of thermal imaging in these studies is predominantly to look for delamination and cracking of the surface at a relatively low depth. Clarke et al. also used thermal imaging to study a masonry arch bridge, with limited results.

Washer et al. (2010) conducted a continuous experiment using polystyrene embedded into a free standing concrete structure, replicating delamination at differing depths of wall. It was found that at certain times of day the differential between the areas with polystyrene and the solid concrete became smaller, so that the areas were harder to see using thermal imaging. This is a similar situation to that found in drystone retaining features with through stones and normal wall construction or voided and non-voided areas; from this you would expect there to be a similar issue, where the distinction between the throughs and voided areas to the normal wall construction will be small. Washer et al. collected between November and January, with the areas of reduced concrete depth predominately showing warmer than the surroundings. This suggests that through stones in particular will show cooler than the surrounding wall. It was also found that during days when there was cloud cover thermal imaging was less effective, which is worth noting when choosing a time to carry out thermal imaging.

7.2.2 Conclusions

Thermal imaging has had relatively little exposure in its uses for structural assessment however extrapolation from previous studies, in particular that carried out by Washer et

al (2010), and from thermal principles, it is likely that thermal imaging will be an effective tool in identifying certain features within drystone retaining walls.

7.3 Field Study

In conjunction with the previously described field studies, a study was carried out to establish if features within or behind the wall, that are not obvious at the wall face, could be indicated by the temperature variations at the wall's surface. Certain features are known to be either advantageous or disadvantageous to the wall. It was believed that it would be possible to detect features through the use of thermal imaging. These features include: through stones, voids, areas of moisture and variations of construction within the same wall. By gaining an indication of where these features may be in the wall, an engineer is able to form a better assessment of the wall's condition and if actions are required.

An initial study was carried out at Northleach, Gloucestershire, to test the feasibility of this technique. Further studies were then carried out in the South of France in the Cevennes area, and on the Ffestiniog Railway in North Wales, covering a wider range of construction styles. Images were taken in a variety of weather conditions and sun exposures, using two different thermal imaging cameras, FLIR B335 and a Mobir M8; they were then analysed on a computer using standard software provided with the cameras. This allows for the visible temperature ranges to be set, down to around a 2°C range, allowing features to be highlighted. Point temperatures and area averages can also be taken.

7.3.1 Northleach

In order to test the feasibility of thermal imaging an initial study was carried out at Northleach, Gloucestershire. The wall supports the south side of the road leading to the A40, East of the village above a field used for grazing, though not at the time of inspection. The area of wall surveyed, though continuous, showed different styles and quality of repair, and so was divided into six sections for the purpose of this assessment. The newest section was constructed in 2011 by Atkins. This wall section was chosen to be the main focus of the study as it is known to be well constructed with obvious

through stones. The other sections are all historic with little known regarding their construction; however they vary both in face style and condition.

The study was carried out over a period of 24 hours between the 6th and 7th June 2013, with images taken approximately every 2 to 3 hours during daylight. This period of time was chosen to allow investigation of the effect of temperature changed throughout the day and night. It was believed that this diurnal cycle, at a time when the temperature difference between day and night was large, would be critical in determining what features would be seen due to differential cooling and heating of stones, caused by contact with the backfill which remains at a steady temperature. A total of 8 different sets of readings were taken within this period using both cameras. The effects of direct sunlight heating the face of the wall were also observed. As well as investigating hypotheses about thermal behaviour, this investigation was expected to inform guidance regarding the best time of day for thermal imaging of walls. The sections imaged are briefly described below Figure 7.1:

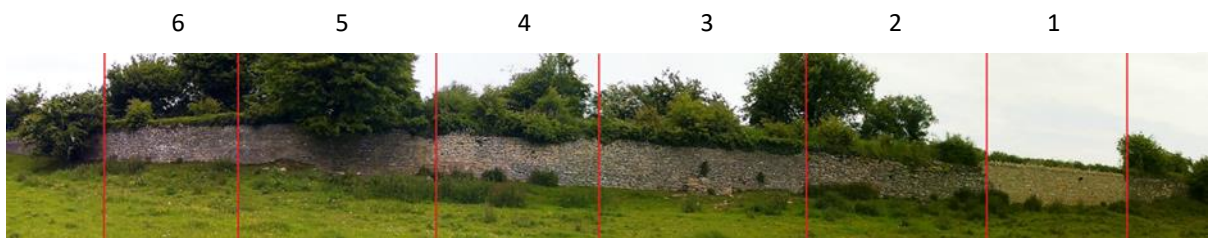


Figure 7.1: Northleach Wall Sections – see below for individual photos

Section 1: This is the new section built in 2011. The through stones in this section are massively oversized and easily visible at the wall face. The fill behind the wall is also known to be well compacted and of good quality, so can be assumed to be in full contact with the rear of the wall. There are also drainage pipes situated within the wall, and an outfall from the road. Unusually there are also layers of soil reinforcement geogrids within the backfill at regular vertical intervals, secured to the wall using metal hooks.



Figure 7.2: Northleach Wall section 1



Figure 7.3: Example of geogrid tie being installed into wall section 1

Section 2: This section has a lot of weathering present and re-deposition of calcite at the wall face. Weathering is mainly concentrated at the edge of stones. This section also has an area of missing masonry within it, which may have been intentionally constructed as an alcove, although similar features were not obvious in other areas of the wall.



Figure 7.4: Northleach Wall section 2

Section 3: This section has a large area of historic repair, constructed using smaller tighter stones than those around it, which do not show any obvious signs of weathering. There are also two areas of vegetation growth within the wall itself.



Figure 7.5: Northleach Wall section 3

Section 4: This section is weathered in a similar way to that in section 2



Figure 7.6: Nothleach Wall section 4

Section 5: This section is heavily mortared and is shaded throughout the day by a mature tree growing on top of the wall adjacent to the road. Little if any direct sunlight reaches this section. As well as being heavily mortared the construction appears to be different to section 2, 3 and 4 with the individual stones appearing to be thicker with a greater aspect ratio at the wall face.

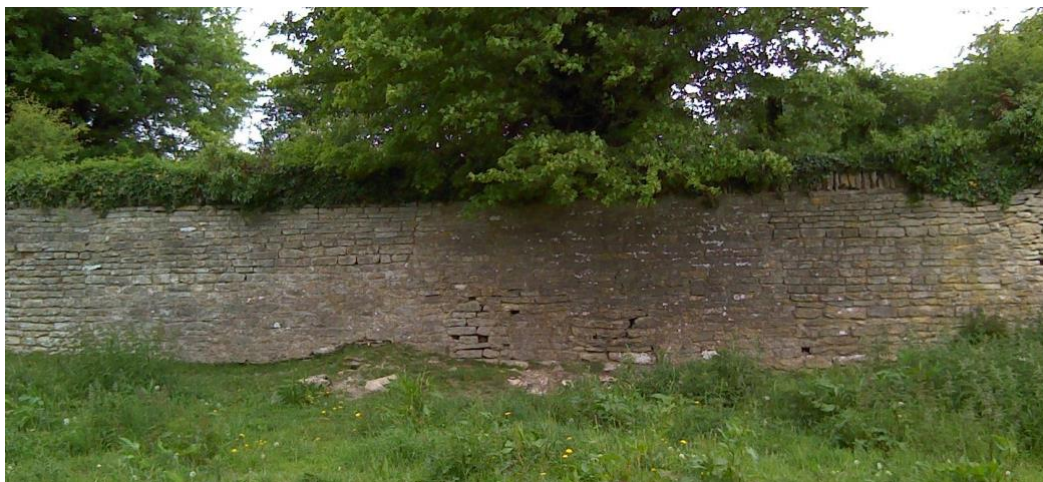


Figure 7.7: Northleach Wall section 5

Section 6: Similar in style to section 5, this section has some mortar present and is far less weathered than section 2 and 4.



Figure 7.8: Northleach Wall section 6

For the entire length of the wall surveyed the ground is banked up against the base. Except the severe weathering in parts, the wall also appears to be in good condition with no obvious signs of large bulges or other features that may be of concern.

Imaging along with observations on the weather and sun positioning, in relation to the wall, took approximately 10 minutes. The main observations along with some of the images taken are shown below. For a full set of thermal and visual images see Appendix 5.

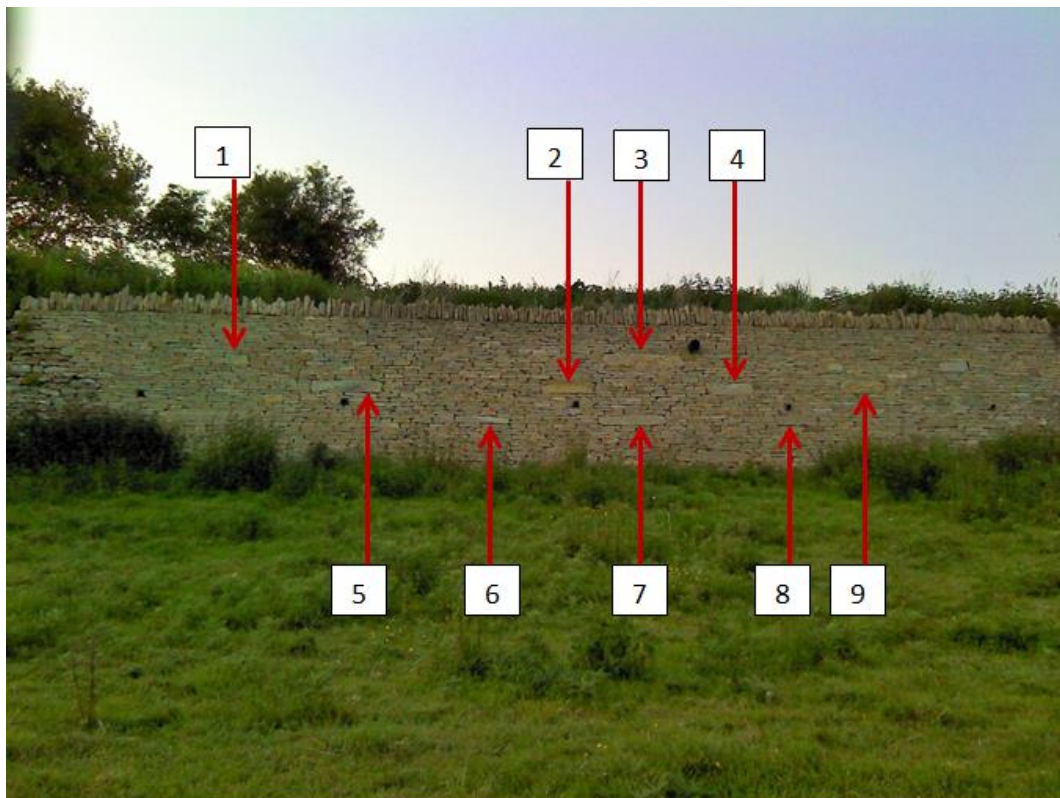
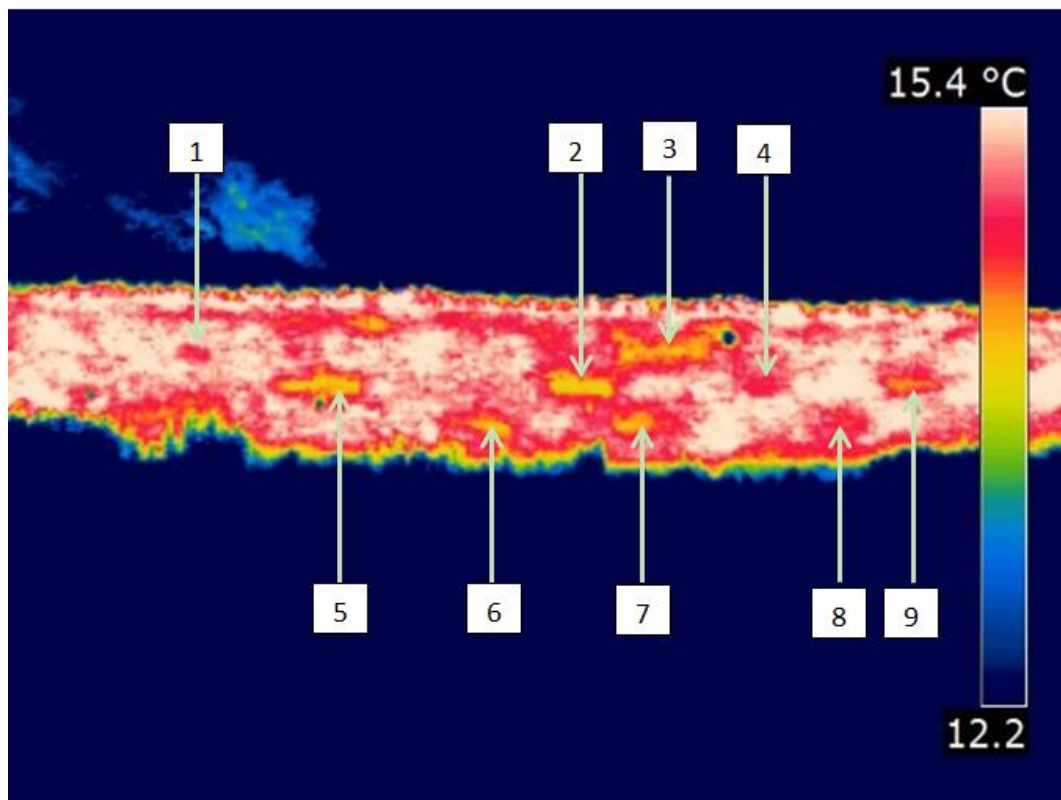


Figure 7.9: Northleach Wall Section 1 – Image taken 06/06/2013 at 20:00hrs when the wall was no longer exposed to direct sunlight. The through stones which are also visible (1-9) in the visual image can be seen to be cooler than the surrounding wall by approximately 1.5degC. This image forms part of the data set shown in Figure 7.10.

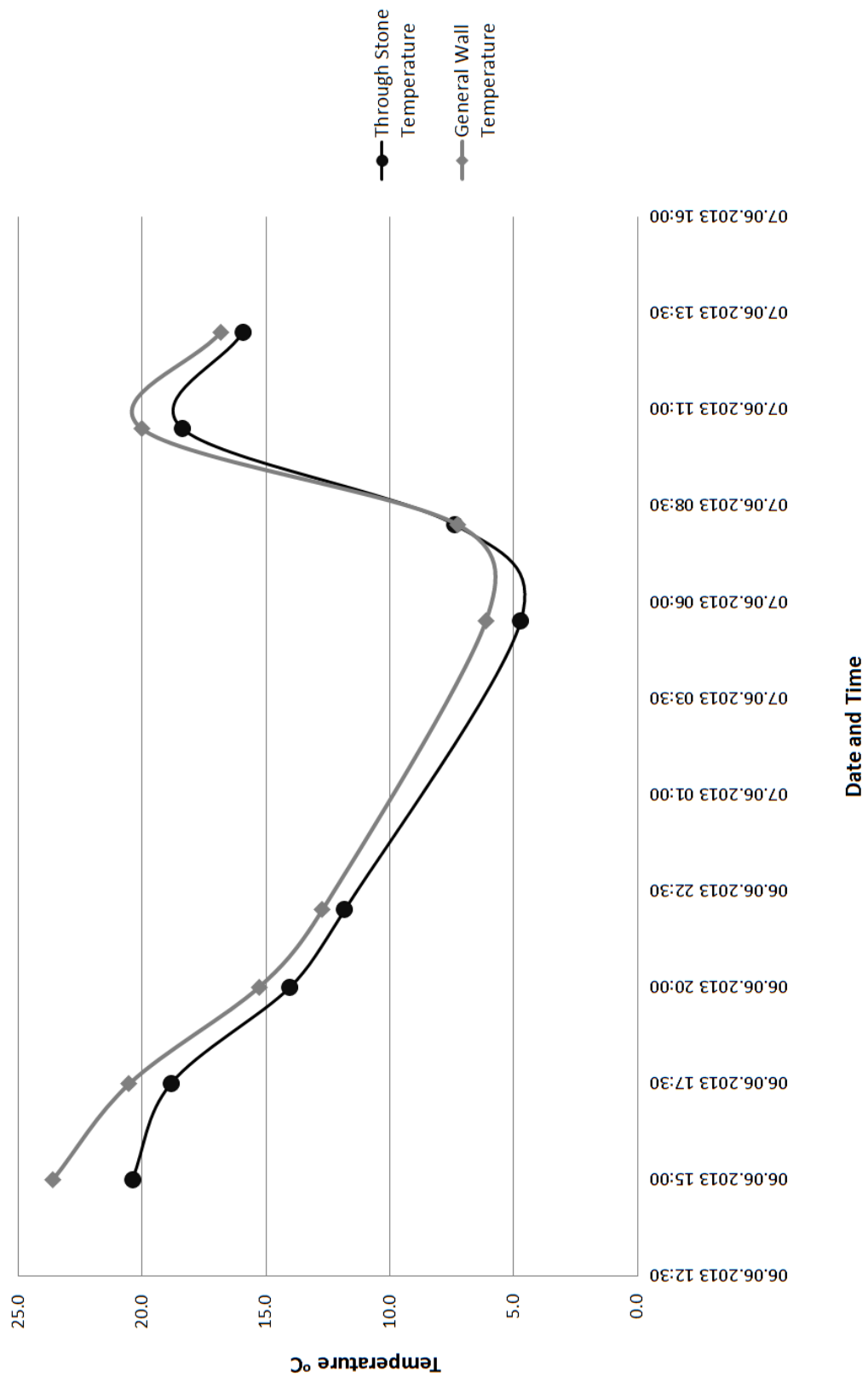


Figure 7.10: Wall Section 1 – Temperature comparison between through stones and general wall construction based on thermal images taken over 06/06/2013 to 07/06/2013.

The image in Figure 7.9 was taken at 20:00 on 06.06.2013 once the wall was no longer exposed to direct sunlight. In this image the majority of the through stones apparent in visible light are also obvious in infra-red, appearing cooler than the surrounding wall. This trend was seen throughout the majority of images taken across the 24 hours. However in images taken around the time direct sunlight is first present on the wall, the through stone temperatures were seen to be very close to that of the surrounding wall. This is shown in Figure 7.10 which shows the recorded temperatures at each time imaged, for both the through stones and the surrounding wall. At 8:00 7.6.15 it can be seen the recorded temperatures were the same for both areas of wall (Figure 7.11). At 13:00 7.06.15 it was also seen that temperature differences are smaller than recorded at most other times. They also do not appear to fit the general trend, assuming a smooth sinusoidal curve would typically be seen over a 24hr period; however, at this time it was recorded that there was full cloud cover, while the time periods prior to this had very little, suggesting the wall was in a period of cooling once direct sunlight had been removed. This initial study implies that imaging could be suitable at most times, avoiding periods of heating or cooling, but that features may be more prominent at certain times of day.

Sections 5 and 6 produced inconclusive results showing very little clear information when imaged (Figure 7.12). These were the only sections of this wall to be mortared and it suggests that the mortaring of the wall has had an effect on the thermal imaging of these sections, rendering this technique unviable for areas of mortared wall. It may also be that the effects of the shading from the tree above has affected the usefulness of thermal imaging in this section. No other wall imaged during this study had obviously been mortared, so the study is unable to confirm these findings.

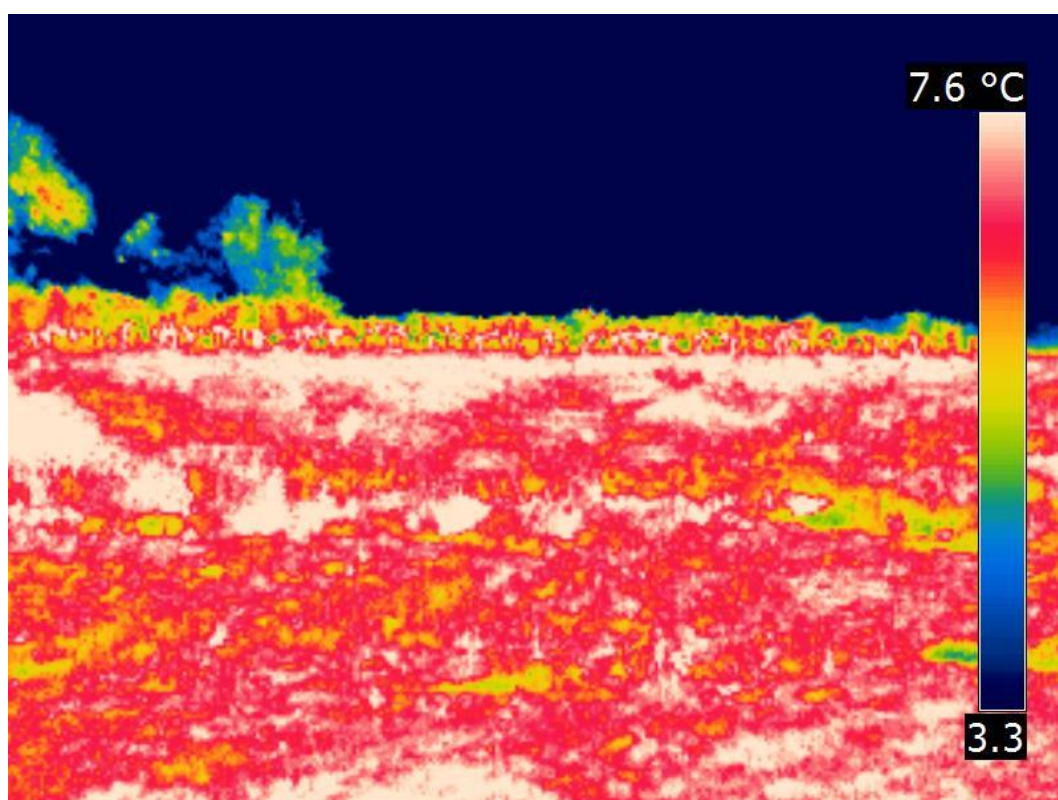


Figure 7.11 Northleach Wall Section 1 – taken at 08:00 07.06.15 Showing small temperature differences between the through stones and general construction.

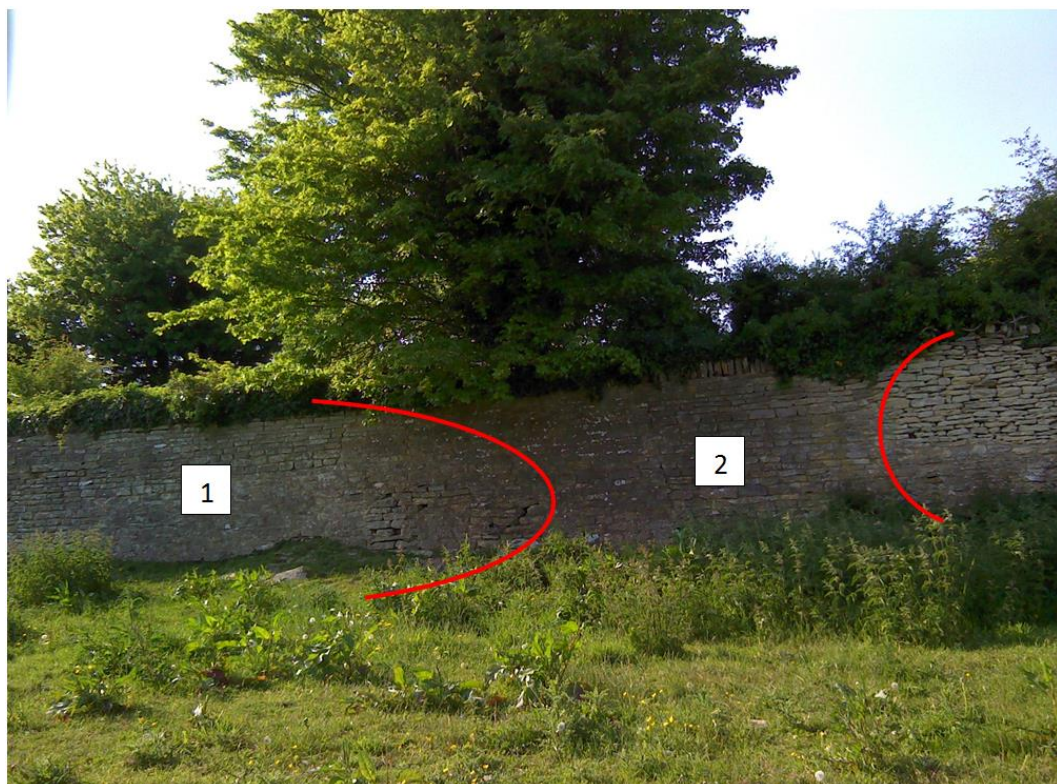
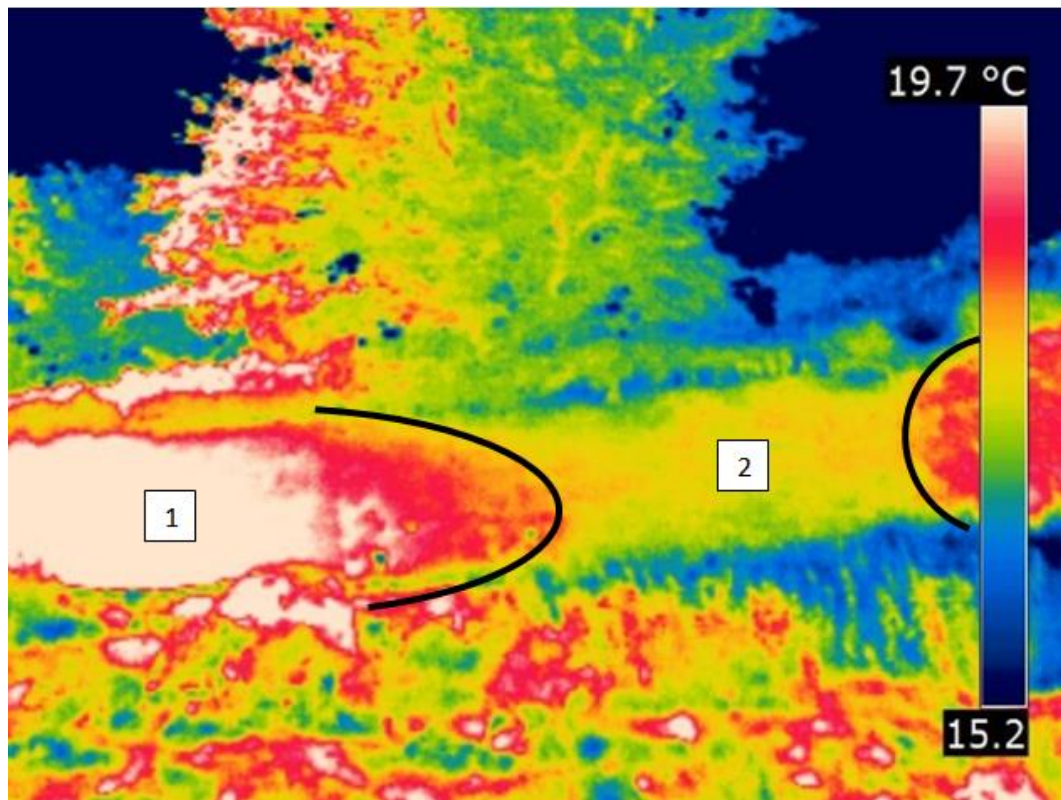


Figure 7.12: Northleach Wall Section 5/6. Image taken 06.06.2013 at 17:30. This is representative of the type of image recorded at this wall section at all imaging intervals. These effects are most likely due to the heavy mortaring (1&2) and near continuous shade from the tree (2).

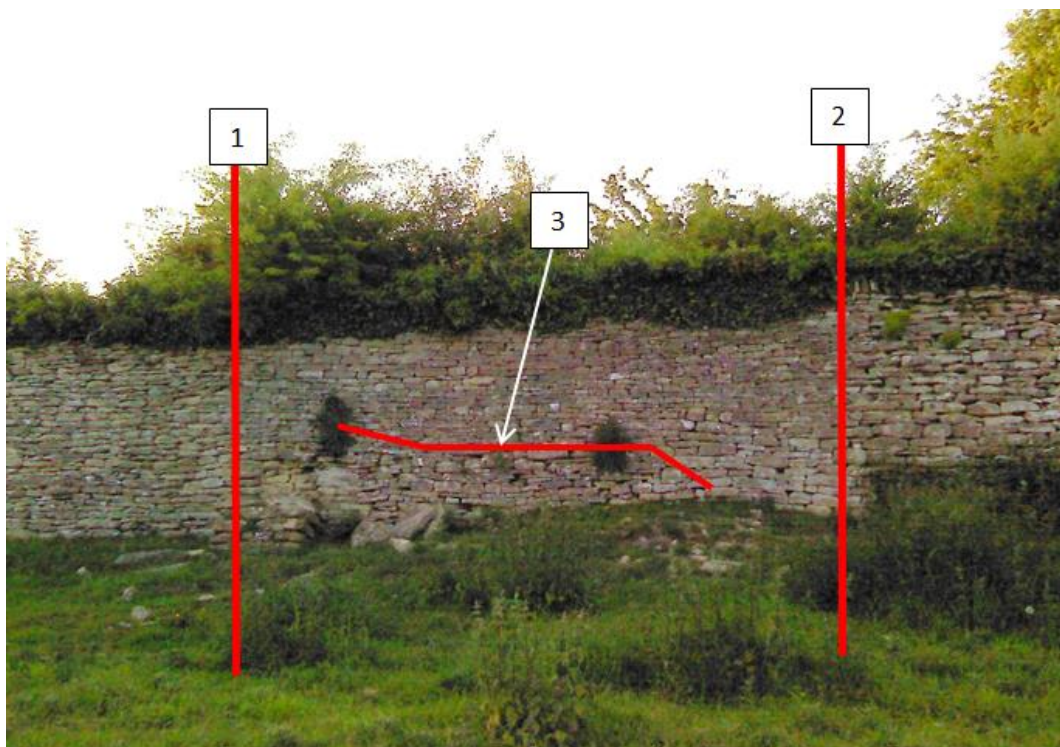
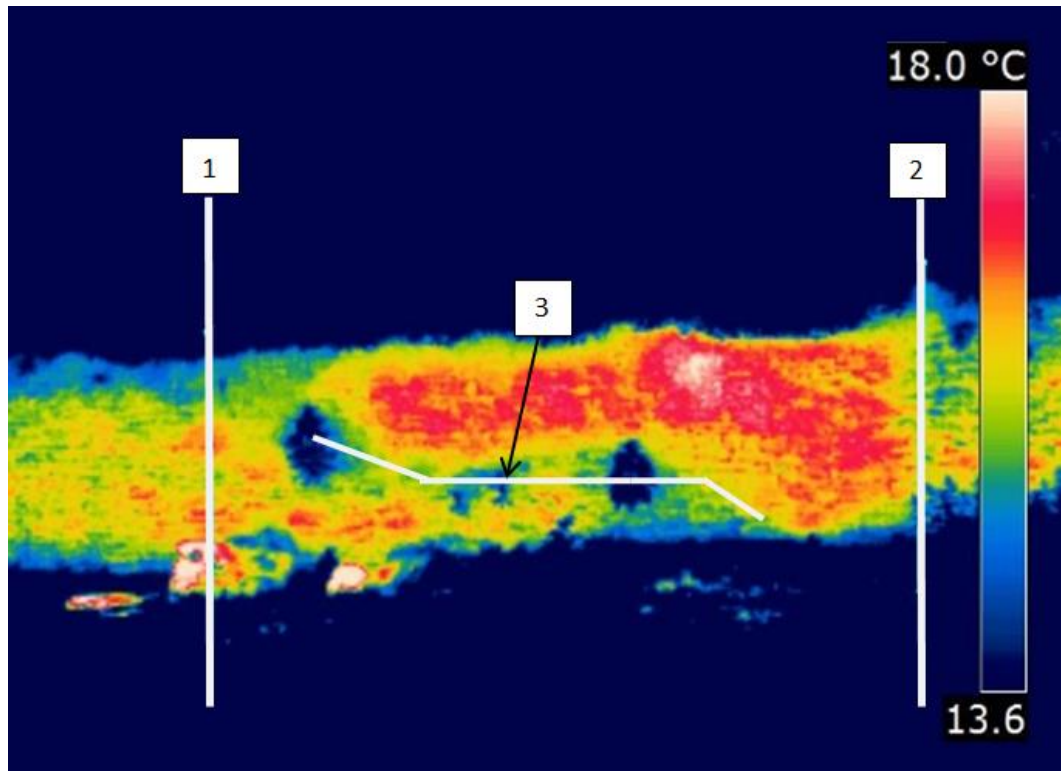


Figure 7.13: Northleach Wall Section 3. Image taken 06/06/2013 at 20:00. In the image it is possible to see temperature changes where the face construction changes (lines 1&2), as well as a cooler area between the two patches of vegetation (line 3), evidence of which is not evident at the wall surface.

Within section 3 a cooler area could be seen, (Figure 7.13) though it was less visible during the middle of the day when direct sunlight was present on the wall. This cool area extends between two areas of vegetation on the wall face; an obvious reason for this cooler area would be moisture at the wall face, which due to its higher specific heat capacity would appear cooler. However there were no obvious signs of damp patches at the wall face, indicating this area would warrant further investigation should the wall be being assessed.

7.3.1.1 Conclusions

From the above observations it was determined that thermal imaging is useful in enabling the identification of features within the wall, such as through stones, as well as other areas of interest that may require further investigation, as shown in Figure 7.13 where a cool area between patches of vegetation was identified. It also determined that certain times of day are better to see these features, for building physics applications it is commonly recommended that just prior to sunrise is often the best times for thermal imaging. This study has shown that while good results can be obtained during this period, other times of day are also likely to be suitable to identify features, which will typically be more practical to fit into a typical working day, and to combine with a visual inspection which often requires good light conditions. The study also suggests times of day that should be avoided as the temperature differences between constructions is at their least; these are periods of heating and cooling typically occurring as direct sunlight onto the wall increases or decreases along with changes in air temperature.

7.3.2 Cevennes, France

The Cevennes study was principally carried out to look at style variations, as described in 3.3, and determine if thermal imaging is useful for a range of different construction styles.

As described in 3.3 the walls in this area are constructed using larger stones than typically found in a large proportion of the UK, and in a more continuous fashion without smaller fill material between two wall faces. This area also allowed thermal imaging to be carried out upon various common stone types including slates/shales and granitic materials, as well as walls constructed using mixed materials.

Images were taken between the 6th and 7th September 2013 at various times of day as the schedule of the visit allowed. A number of walls were imaged and the further images can be found in Appendix 5 and on attached CD should the reader wish to explore the findings in greater depth than presented in this chapter. The majority of the walls imaged were recently constructed, and local wallers were able to provide information regarding their general construction practices; older walls were also imaged. Due to the nature of the analysis, with the thermal images being edited on return to the UK, it was not possible to fully verify the finding with the wallers that constructed these walls. However, some of the images taken are shown below, along with potential reasoning for what has been seen.

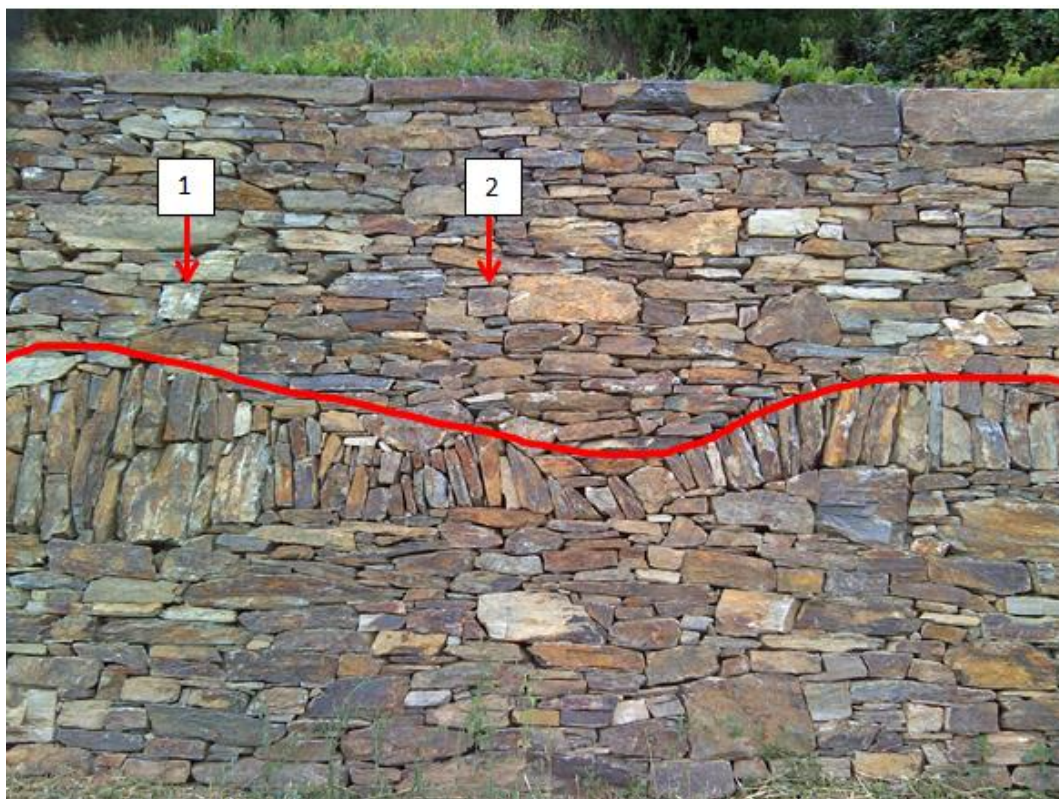
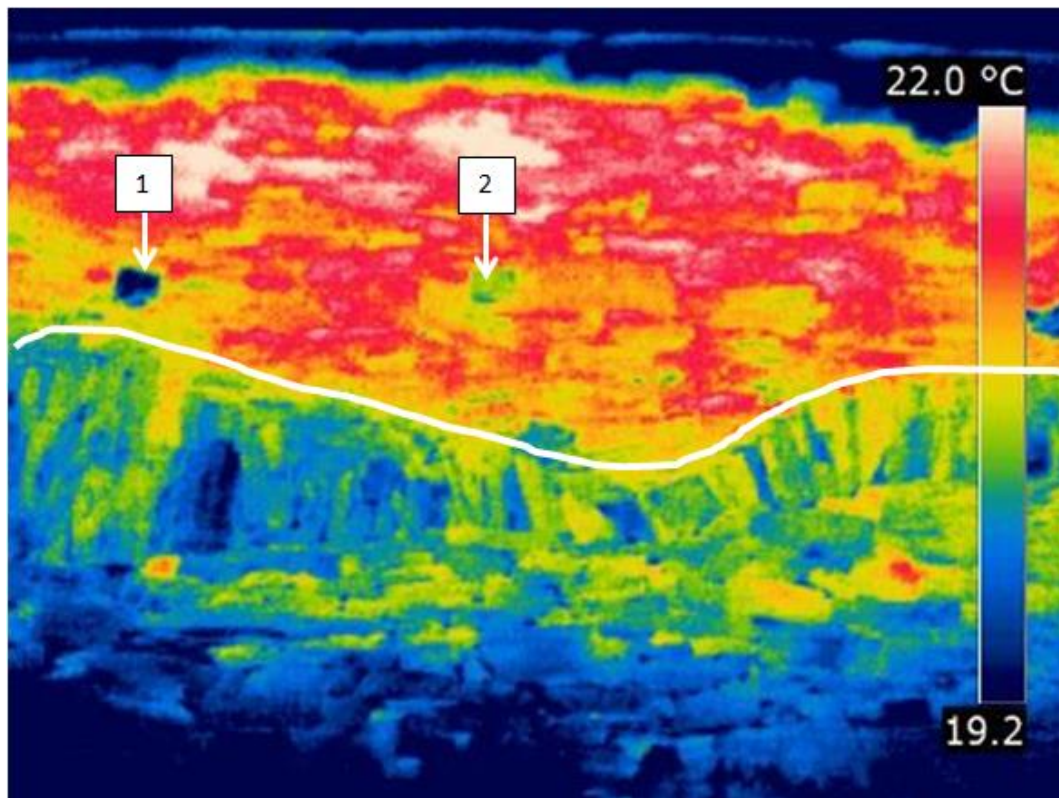


Figure 7.14: 3m High, North Facing Wall in L'Espinas on the D45, France. Situated on Private property Taken 10.55 07/09/2013. Showing potential through stones that are not obvious at the face (1&2), and the obvious temperature difference between the top and bottom of the wall face, indicating at differences in material behind wall.

The wall in Figure 7.14 is constructed of schist quarried at the site of the wall. The images were taken at 10.55am. The most striking feature is the clear temperature difference between the top and bottom of the wall. At the face of the wall this boundary is denoted by a decorative band of vertical stones. It is likely that this band serves a dual purpose, being both decorative and defining the level of the bedrock behind the wall, which would also explain the temperature difference between these two sections. From talking to the wallers this wall is constructed from stone quarried within the property boundaries, hence the bedrock will be found at a shallow depth making it plausible that the lower level of this wall is built against a bedrock layer.

It is also possible to see two distinctly cooler blocks in the top section of the wall that were immediately obvious in the image on site. In discussion with the wallers who constructed the wall they confirmed that these stones penetrate into the wall in a similar fashion to a through stone. Good local construction practise dictates long narrow stones are typically placed across the width of the wall, hence, penetrating further into the wall. To place them with their long faces along the wall would greatly reduce the face stability as these stones are more likely to rotate under loading. Their smaller face size in comparison to some of the other stones in the wall may lead to them being passed over in an inspection as being irrelevant to the wall stability, as it would often be assumed in a wall such as this, where a number of different stone sizes are found, that it would be the larger ones that would span the depth of the wall and hence act as through stones. It is also possible to identify a number of other cooler stones which may indicate that these stones penetrate to a greater depth within the wall. There are also areas that are significantly warmer; when compared to the visual image these warmer areas typically coincide with clusters of smaller and narrower stones at the face.

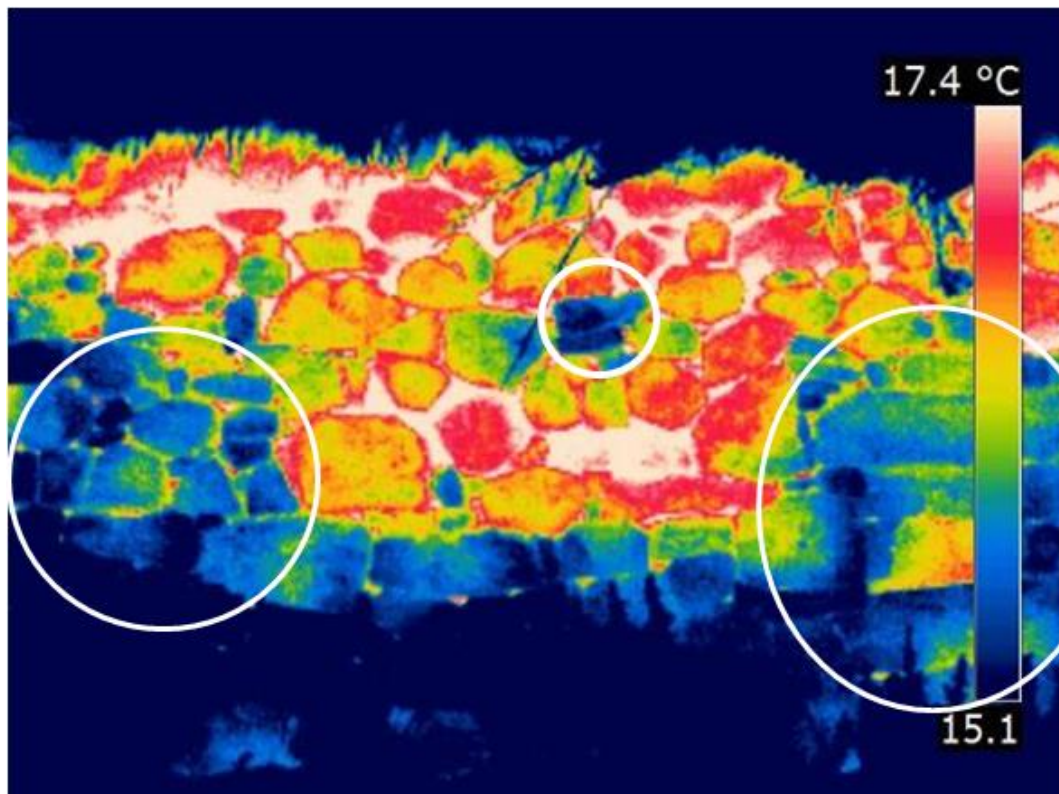


Figure 7.15: 3m High, South West facing teaching wall in Le Pont-de-Monvert, France, Situated next to a small road. Image taken 08:00 07/09/2013. Highlighting cooler wall areas.

The wall shown in Figure 7.15 is constructed of large granite stones and was constructed as a teaching wall. The wallers that aided in its construction consider it to not be of high quality, although strong and stable. This image was taken around 08:00 before the sun was directly onto the wall. The cooler area to the right corresponds to an alcove within the wall. A cooler section can be seen to the left of the image as well as one significantly cooler area in the centre of the warmer section. The study carried out at Northleach would suggest these cooler areas are representative of stones that are in greater contact with the backfill, as well as suggesting that the warmer areas are not in such good contact with the backfill. However, when comparing the stones in the centre of the image to the surrounding stones, these stones appear smaller and are likely to not be in such good contact with the backfill. At the time of year this image was taken, large difference between day and night temperatures occurred, with potential for frosts in the mornings and day time temperatures the high 20s. This thermal image was taken early in the morning before the effects of daytime warming could occur. As such the smaller stones in less contact with the backfill are more effected by the night time cooling than the larger stones with greater contact with the, at this time, comparatively warm backfill.

The construction type with large more rounded stones is also likely effect thermal imaged produced when compared to more blocky linear construction. It is likely that though the construction appears relatively tight at the face, there are larger voids behind with pinnings to hold the stones in place, with further large stones behind this which carry out the task of retaining the soil, Figure 7.16 shows the wall under construction and the nature of the stone used. This will also give a reduced contact area when compared to the contact seen between blocky stones, reducing heat transfer within the wall. The voiding combined with reduced heat transfer could be resulting in a similar pattern in the thermal image to that which would be produced if the wall were not in good contact with the backfill, whereas the main issue is likely to be poor thermal conductivity of the wall itself. This image highlights the importance of combining this with a visual inspection, and not using thermal imaging as a sole method of assessment. It also makes clear the importance of understanding variation in stone types used in wall construction.



Figure 7.16: Le Pont-de-Monvert teaching wall under construction showing nature of stones used (McCombie et al. 2016)

The wall in Figure 7.17 is constructed mainly from schist materials. This image was taken at 10:40. This image highlights how variations in the stone colour can affect the results seen using thermal imaging. The large cooler area to the left of the image represents a feature constructed of white stone in comparison to the darker, warmer stones around it as can be seen in the visual image. Typically, walls are constructed of a single stone type that are all a similar colour with similar thermal properties, however in some areas of varied geology such as in this Case, walls can be constructed of stones with significantly different thermal properties, which needs to be taken into consideration. Different stone types are often easily picked out during visual inspections, again showing that thermal imaging needs to be used in conjunction with visual inspections.

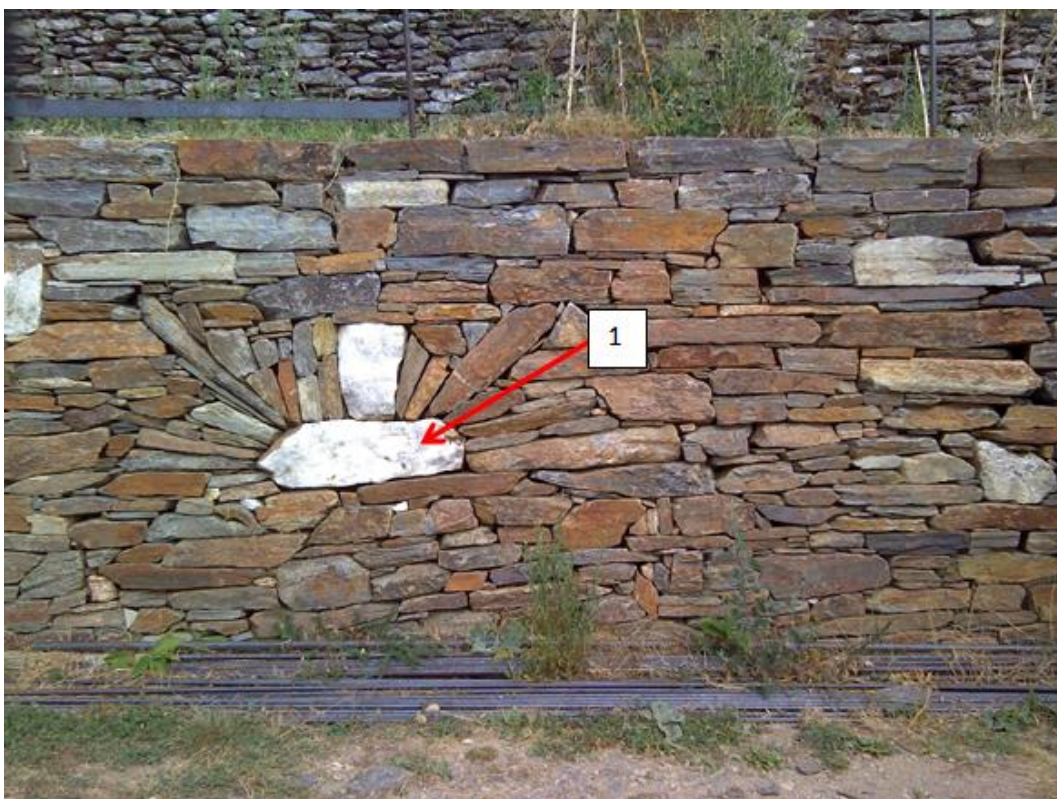
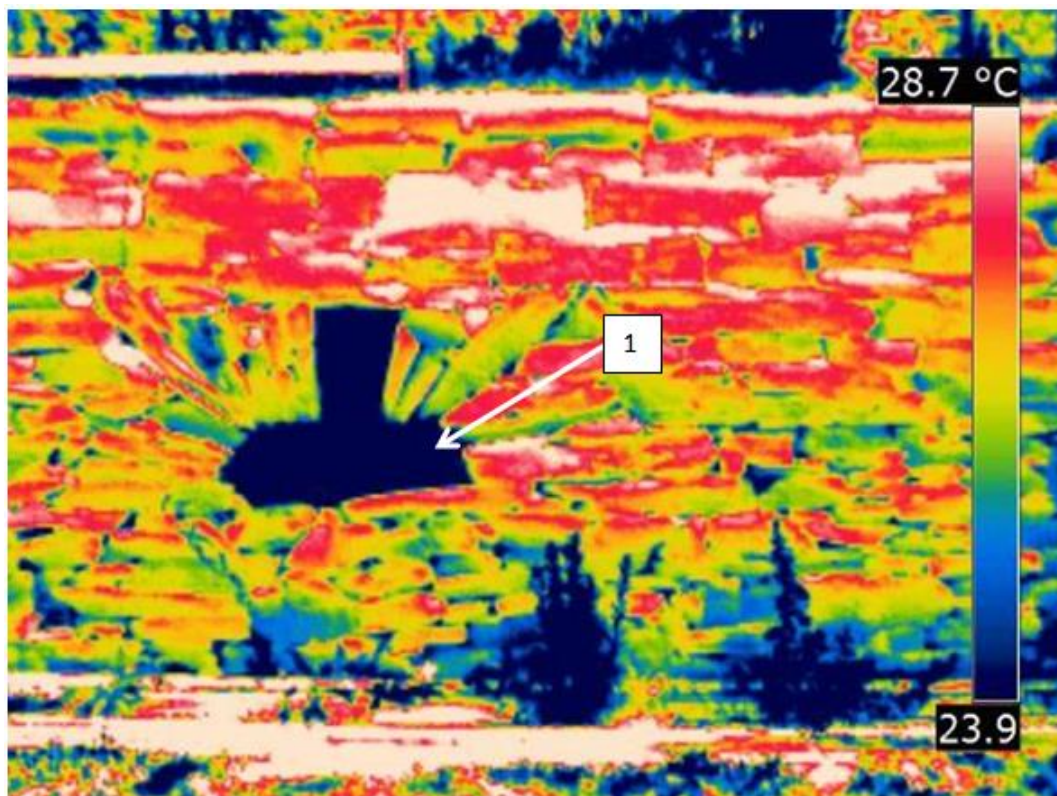


Figure 7.17: 1.9m high, south facing wall in L'Espagne on the D35, Supporting terracing. Image taken 10:40 07/09/2013. Showing the effects of differing stone colour on thermal imaging.

7.3.2.1 Conclusions

The French walls provided an opportunity to image walls constructed of varying materials and construction styles, which are not as prominent within the UK: these were predominantly constructions involving larger stones, both worked and unworked. The work has shown that in some cases stones that appear to be small at the face but extend into the wall aiding stability may be picked up using thermal imaging. However, it has also shown that care in making the assumption that cooler stones, especially when smaller in size, may not always be right. In these cases the time of day; temperatures leading up to the time of the image and construction style need to be considered, as well as undertaking a detailed visual inspection of the areas of concern.

By using visual inspection and visual images alongside thermal imaging it also makes it possible to identify any anomalies that have produced potentially misleading thermal features, such as the variation in stone type and colour producing cooler images that may be associated with through stones.

It also highlights the importance of stone shape and its influence on thermal imaging, and that stones that cannot easily be worked, such as granite, may give misleading or unexpected results.

7.3.3 Ffestiniog Railway, North Wales

The Ffestiniog railway produced an opportunity to use the thermal imaging camera on drystone structures completely different to those seen in Northleach and in France. The drystone found here is in the form of massive embankments used to support the railway and uses stones far larger than seen in other locations visited, see 3.2.3 with many of the embankment walls over 3m in height.

The embankments on the railway also have many historic modifications including buttressing, widening, and realignment of the track at various points, which potentially means there could be multiple layers of stone with them. Little is known about their internal construction, and there are culverts that run under the embankments in many places. The walls are predominately constructed using schist and slates sourced locally.

This image (Figure 7.18) was taken at 17:00. This double-sided embankment is 19m high with a minimum width of 2m at track level. It is possible that it might have been constructed in a manner to resemble a massive freestanding drystone wall. Only the north facing side was imaged. Being north facing there was no direct sunlight; it is also surrounded by trees. However, it is possible to see that some of the stones within the wall appear warmer than those around them as shown above. As the photograph was taken at 5 p.m., it is likely that the south side was significantly warmer than the north side, implying a temperature gradient between the two. These stones also appear to be larger than the stones around them; if they project deeper into the wall, and closer to the south face, then this would explain them being warmer, as the large intact stones would conduct heat better than the surrounding small stones with many voids between them. This has implications for through stones on north facing retaining walls where the constant temperature of the backfill may cause the temperatures to be different to the stones surrounding them, as well as having the effect of heating and cooling by air contact at different rates to smaller stones within the wall.

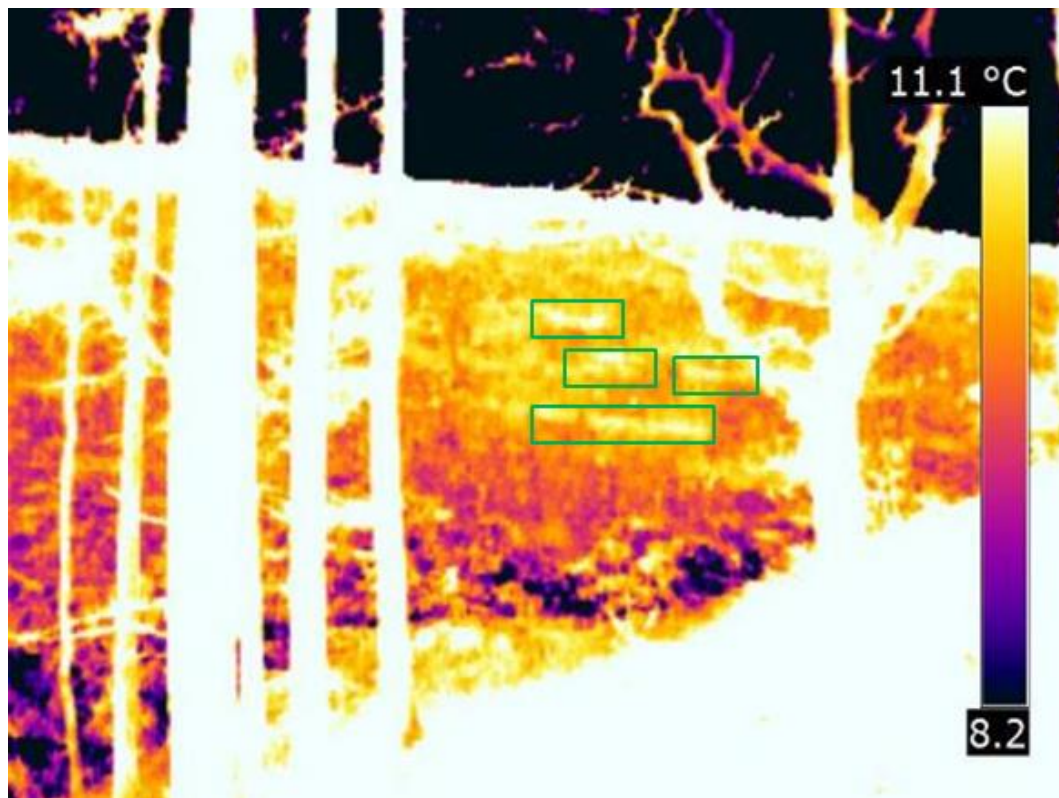


Figure 7.18: Cei Mawr, North facing side of railway embankment. Image taken 17:00 01/04/2014. Slight temperature differences can be seen (highlighted) which may indicate toward construction variations.

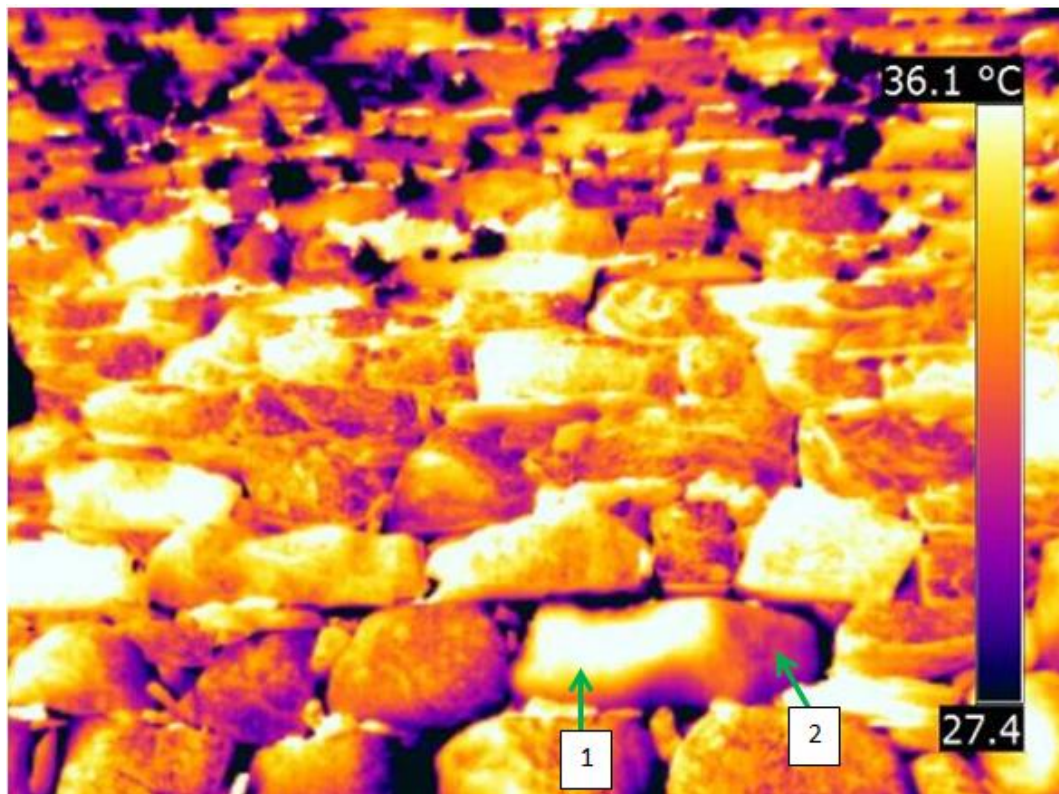


Figure 7.19: Between Tanybwllch and Dduallt, South-South East facing, supports railway. Image taken 14:00 01/04/2014. Showing the effects of stone face angle in the wall. From the shadow the direction of the sun can clearly be seen. The stone face facing the sun (1) is significantly warmer than that not (2). An effect seen on many of the stones in this image.

This image in Figure 7.19 was taken at 14:00 and shows how the small variations in the angle of the face of the stone can cause temperature variations across the stone surface as it has varying amounts of direct sunlight. This is particularly noticeable in the stone in the bottom right of the thermal image (highlighted). From the shadow on the wall it is possible to see that the direct sunlight is from the left of the image. The warmest section of the stone (1) can be seen angled toward this giving it the greatest direct solar gains at this time, whereas section (2) although not shaded can be seen to be facing away from this direct sunlight and hence appearing significantly cooler than section (1). This stone has the most prominent variation in its face orientations compared to the other stones within this wall, though the effect can be seen to a lesser extent on some of the other stones when comparing the visual and thermal images. This image highlights the potential of direct sunlight on a wall making the interpretation of thermal images more difficult, as it suggests the angle of the stone to the sun has an effect on the readings produced. Where the majority of walls are constructed with stones that have been shaped, and therefore nominally the whole stone face is in one direction to give a more aesthetic appearance, is it possible that this effect may not have as much influence. However, the potential for direct sunlight should be considered, particularly where walls are constructed using unfinished or unshaped stones. This suggests that early in the morning, or later in the evening may be better suited to imaging some walls with particular characteristics, or alternatively days which are overcast. This effect may also be due to the sun angle at this time in relation to the wall; were the sun angle nearer 90° this effect may not be so acute.

7.3.3.1 Conclusions

The work carried out at the Ffestiniog railway has shown that thermal imaging may be possible where the wall is never subjected to direct sunlight. It also highlights that care needs be taken to ensure that the temperature variations seen are not due to the stone roughness and local variations in stone orientation. However by consideration of the time of day when images are taken this effect could be reduced, by ensuring direct sunlight is not able to affect the thermal readings - i.e. during periods when direct sunlight is not on the wall, this will vary according to wall orientation.

7.3.4 Conclusions

From the field work carried out it is clear that thermal imaging could provide a useful tool in the assessment of drystone walls. It has shown that potential through stones, or the lack thereof, can be detected in a number of walling styles. The work also demonstrates the ability to pick out stones at the face which extend into the wall that you would not obviously assume to be of a through type, due to their smaller face size, such as those seen in France. However, it also highlights the care that needs to be taken to ensure features, especially those where stones are of a smaller face size, are not misidentified, as they are more likely to be affected by the daily temperature changes, due to their lower thermal mass, than any larger stones surrounding them. It also shows potential to pick up other features within a wall, and potentially water build up. The work has also shown that thermal imaging can be used on walls in any orientation without the need for direct sunlight.

However, the work has highlighted some issues that need to be considered when looking at thermal images. There are a number of factors that may give misleading thermal results, such as the slight variations in the angle of the stone face, making certain areas appear warmer than others. The stone shape behind the face may also lead to thermal isolation of face stones giving misleading results. Care must also be taken when a wall is constructed using differing stone types that have different thermal properties, most easily identified by differing colours. These issues show the importance of using thermal imaging in conjunction with visual inspections.

In order to investigate thermal imaging further, modelling of basic walling constructions is carried out.

7.4 Thermal Modelling

A number of 1D thermal simulations were carried out, in order to be able to better analyse thermal images taken of walls, using WUFI, a commercially available thermal simulation program often used to model the thermal performance of building skins. This program was chosen over hand calculations as it enables a large volume of simulations to be carried out in a short time period. It also enables simulations to be carried out using actual weather data, therefore weather data from near the Northleach wall for 2013 (Brize Norton Airfield) could be entered into the simulation, allowing for direct comparisons between the field study and the thermal simulation.

WUFI works by evaluating the changes in temperature and moisture, within discrete time steps, from given starting conditions. During this process it takes boundary conditions from climate data provided. There are three mechanisms which WUFI uses to produce the output data: heat transport, vapour transport and liquid transport.

In the calculation of heat transport, the software takes into account the following variables (Wufi-wiki n.d.):

- Thermal conduction
- Enthalpy flows through the moisture movement with phase change – Evaporation and condensation.
- Short-wave solar radiation
- Night-time long-wave radiation cooling

Simulations were carried out to mimic a number of different stone arrangements often found in walls across the UK, as well as in France (Figure 7.20). A number of these will often be found within a single wall. By determining how face temperature differs between arrangements it will help identify them when using thermal imaging to assess a wall's structure. In total 6 different constructions were simulated.

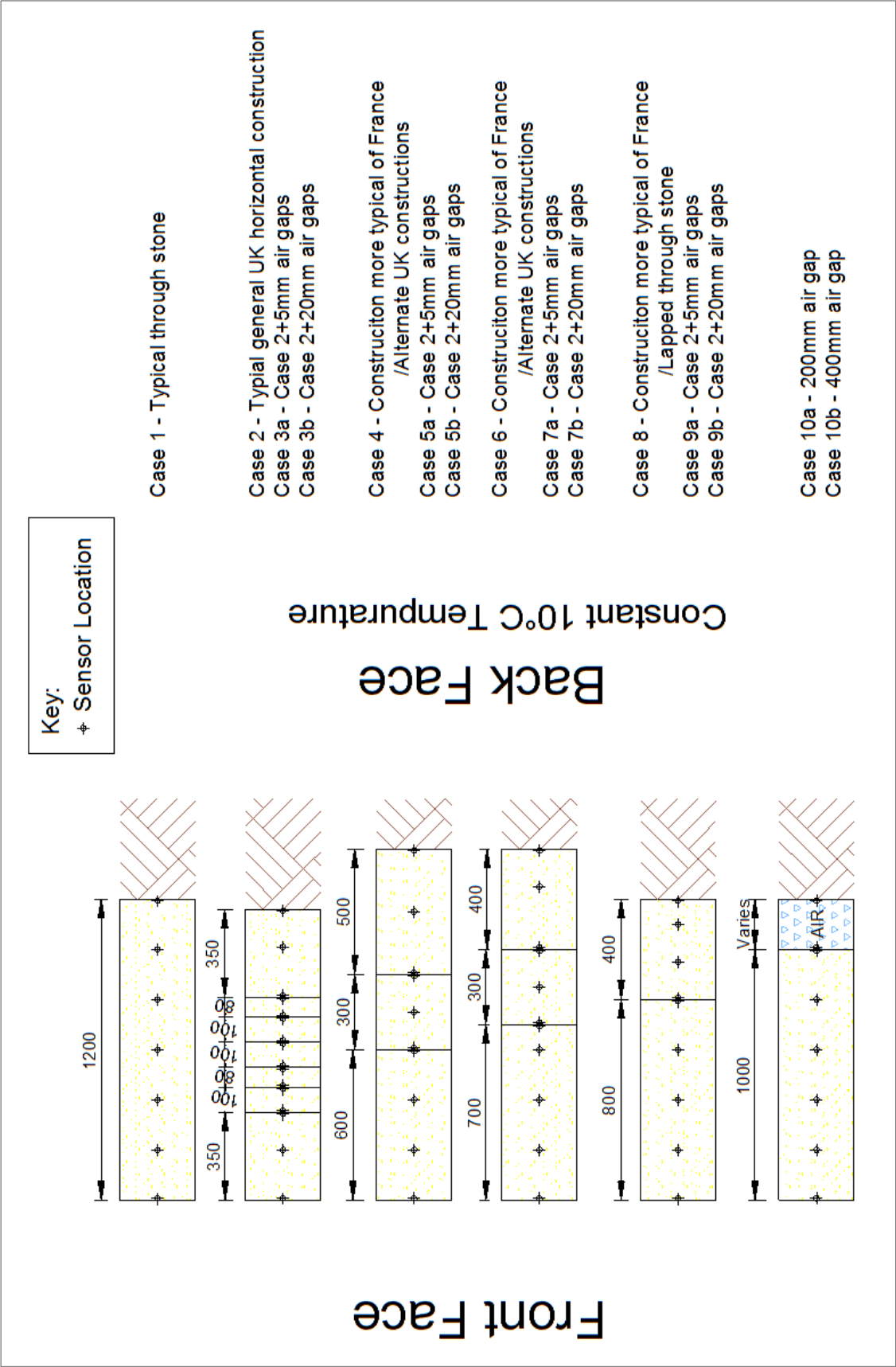


Figure 7.20: Stone arrangements modelled using WUFI

Cases 1 and 2 represent the two main constructions found in a typically constructed wall within the UK, Case one representing a through stone and Case two representing a double skinned construction with fill between. Cases 4, 6 and 8 represent constructions that were typically seen in France where continuous construction is more popular; this type of stone placement may also be seen in the UK where vertical construction is in use or where a through stone has cracked due to concentrated stresses upon it. Case 8 can also be seen where a suitable through stone is not available, so a lapped through has been used and will often have a mirror image of this above or below it to provide a continuous layer through the wall. Case 10 represents a through stone where the backfill has come away from the rear of the wall creating a void. Cases 2, 4, 6 and 8 were also simulated including 5mm (a) and 20mm (b) air gaps (Cases 3, 5, 7 and 9 respectively) in order to simulate the non-perfect contact between stones often found within walls. Where there are multiple larger air gaps such as in Case 3b this could also represent the degradation of fill within a wall which is known to be a common occurrence in older walls, particularly where they are constructed of limestone.

Simulations were carried out for each of the constructions shown in the vertical plane for each of the main four orientations (north south east and west). The simulations were carried out for a period of 3 years using the 2013 weather file with only data for the final year being used, as this allowed for normal trends to form.

The simulations were carried out using a limestone available within the WUFI simulation program itself, which has a database of commonly used building materials based on the ASHRAE Report 1018-RP (Georgian Bay limestone with a bulk density of 2500kg/m^3 , very close to measurements on stone similar to that found in the Northleach wall, (Mundell, 2009). Virtual sensors were placed within the wall at the face of each stone as well as throughout the larger stones. For the purpose of the study only the front face temperatures were used, due the fact that this will be what the thermal imaging cameras detect. However further data is available in Appendix 5 and on the attached CD, and could be used to investigate heat transmission through the wall. The rear of the wall was set at a constant 10°C . In reality at the heights most drystone walls retain soil temperatures will fluctuate with depth and time as shown by García-Suárez and Butler (2006), with the 10°C being closer to temperatures seen at around 15m deep (BGS n.d.). However thermal imaging is seen as a qualitative assessment method, and it was

deemed that a constant 10°C would provide correct qualitative trends, with the variation in temperature across the width of the stone used for direct comparison between the construction styles modelled. Modelling the soil to depth using WUFI would have added additional complexity to the due to the effects of seasonal moisture variations and other soil parameters, which are beyond the scope of this study.

The weather file used for the simulation is taken from actual weather recordings for Brize Norton air field (Weather box n.d.) in the Cotswolds for 2013. Dates throughout the year were chosen to analyse depending on the air temperature conditions. These dates were chosen during and after periods of high temperatures, low temperatures, large and small variations between day and night time temperatures, and when air temperatures were close to the 10°C of the backfill. Simulations were carried out for the four main compass orientations, to assess the influence of orientation on the wall temperature, since this affects the amount of direct solar radiation on the wall face.

The results of the thermal modelling are intended to clarify the general temperature variations seen in the thermal imaging, and to examine the assumptions made in their analysis. It may also add to the features that may be seen, as well as indicating when the best times to use this technique.

7.4.1 Results

Graphs were produced for 75 dates for 24 hour periods, in all four orientations, for the conditions described above. This enabled the different Cases to be directly compared, along with the air temperature, which is considered to be the driving factor of the wall temperature, as well as being the most accessible.

It was found, due to the full contact in the joints, that Cases 2, 4, 6, and 8 produced results very similar at the face to that of Case 1. These results have relevance if larger stones were to crack within the wall, it is however unlikely that this form of joint would be seen. Slight movements due to small voids would mean that a gap would form; it was therefore decided to remove these results from the main analysis. For direct comparison results from Cases 1, 3, 9, and 10 are shown as these represent simulations of comparable width allowing comparisons to be made.

Because thermal imaging is a snapshot, the key feature of the analysis is not the actual temperature of the wall face or the variations over the 24 period, instead the differences across the cases at one particular moment, as this is what the thermal imaging camera would capture.

It was found the orientation of the wall, though it did have an effect on the wall temperature, had little effect on the general temperature differences between the Cases for any given time period Figure 7.21.

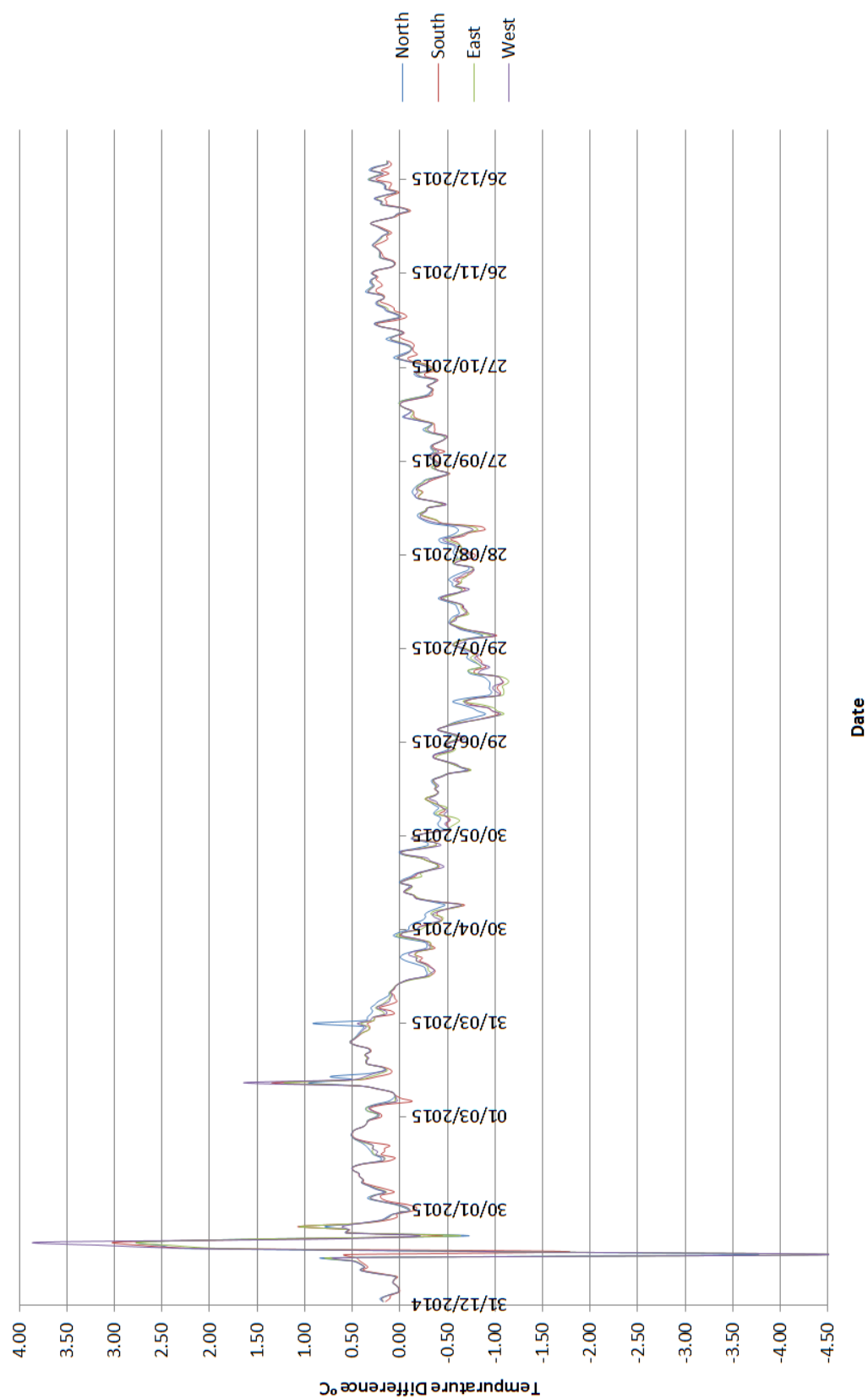


Figure 7.21: Effects of Direction on temperature difference between Case 1 (Typical through stone) and Case 3 with 20mm air gaps (Typical UK wall construction)

The time of day that imaging is shown to be optimal also varied between the different orientations. Some conditions and orientations, particularly north facing walls, showed similar temperature ranges throughout the day. However it was seen that there are three periods of the day which are best to carry out thermal imaging:

- Early morning, before direct sunlight is on the wall
- Around the solar noon, when direct sunlight has been on the wall for a period of time
- Late evening once direct sunlight is no longer on the wall

Figure 7.22 shows the hourly average temperatures for the south simulation across a year. Highlighted are Cases 1 and 3b, which show the greatest differences in temperature at the times of day above, between 05:00 and 06:00, between 13:00 and 15:00, and around 22:00.

This is still shown to be true for north facing walls in the majority of Cases, as reflected radiation still has an effect on the wall.

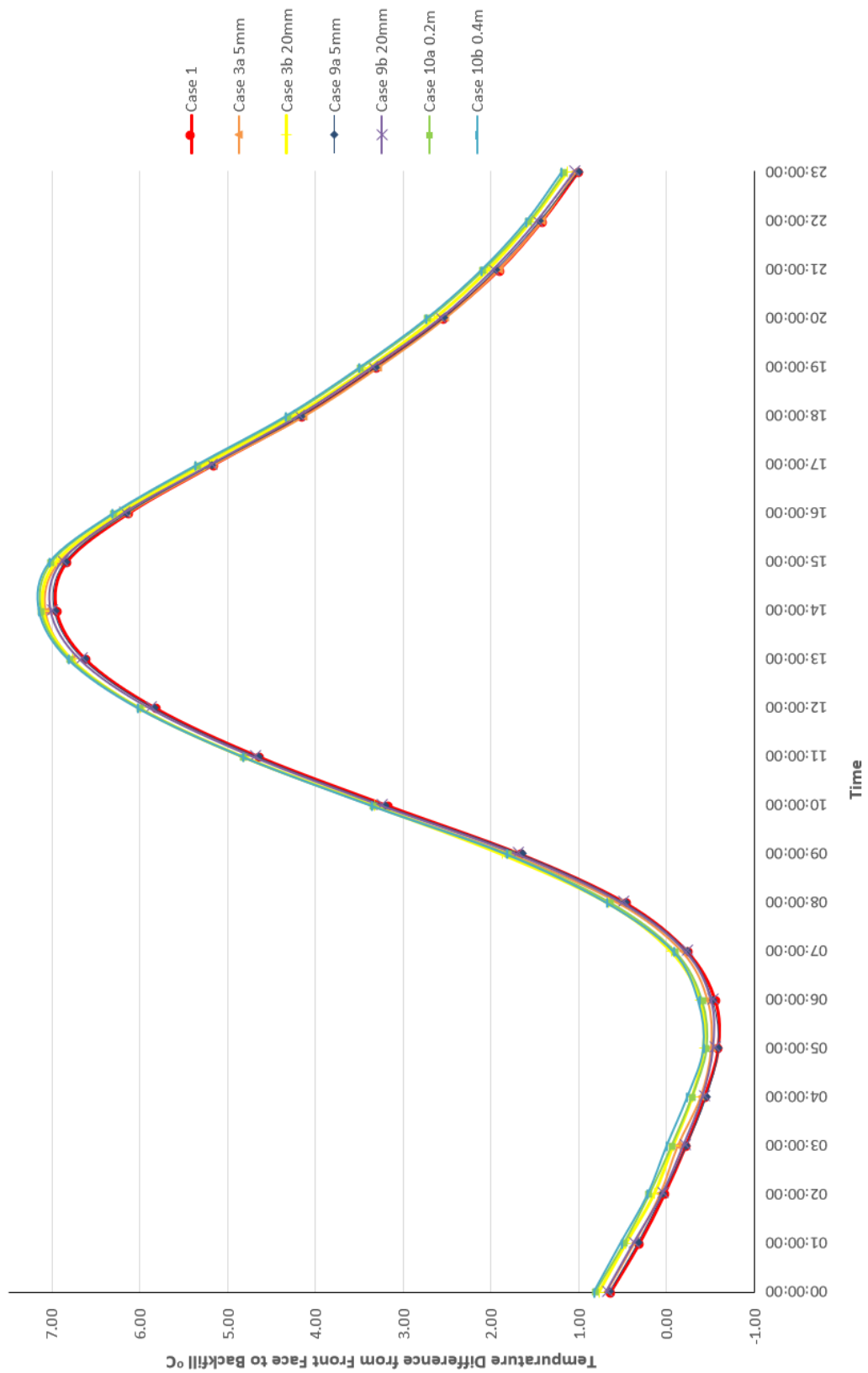


Figure 7.22: Average hourly temperatures over 1 year for each construction type.

Generally, it can be seen that different wall constructions when arranged by their temperature tend to sit in a similar order throughout the year. Generally, constructions with fewer stones sit at one end of this and the constructions with more stones sit at the other end, with the exception of Case 10 which tends to sit at the same end as the constructions with more stones as seen in Figures 7.23-7.26. which you may expect as in constructions with multiple stones, and in Case 10 where there is a significant air gap, decreasing the influence of the backfill compared to constructions of similar sized stones in contact with the backfill.

The time of year also appears to determine whether the constructions sit on the warm or cooler end of the scale, Figure 7.23. During the warmer months, typically mid-May to the beginning of November, Case 1 (typical through stone construction) is typically the coolest case, as you might expect due to its continuous contact with the backfill. Case 10 and Case 3b air gaps are typically warmest, again you may expect Case 10 to be warmer due to the greater heat capacity of a large stone, along with the void insulating the stone from the cooling effects of the backfill. Case 3b, due to the larger air gaps, also effectively isolates the front face from the cooling effect of the backfill (Figure 7.24). During the cooler months, the end of November to mid-April, this is reversed with Case 1 typically the warmest and Cases 10 and 3 being the coolest, again for the same reasons given above (Figure 7.25).

During November and from mid-April to mid-May (Figure 7.26) a period of transition occurs where the differences in the temperatures between the construction styles becomes smaller and the temperature patterns are less predictable. Typically, Case 3 is the first case to respond to these temperature changes, with Case 10 being the last key marker to respond. During these transition periods the air temperature is similar to the backfill temperature. The timing of these transition periods is likely to vary in the field due to differences in both climate and backfill temperatures.

Although during the transition periods temperatures between the different cases are similar, a temperature difference between Case 1 and Case 3 can still be seen. These are the most commonly seen form of horizontal construction within the UK, and are the 2 most important cases, as they represent standard horizontal construction and through stones. However, the temperature differences seen, assuming the simulations are a fair representation of the actual temperatures differences found, it still may be difficult to

see these using thermal imaging, despite its high sensitivity. Case 9 is also often found to be very similar in temperature to Case 1, however this is often used where a full thickness stone is not available and in terms of wall stability offers a very similar effect, hence the similarity in temperature is not an issue.

Though not shown Cases 5 and 7 were seen to be generally similar to each other and fall in the middle of the temperature range between the warmest and coolest constructions. These along with Case 9 and Case 1 are typical to the constructions seen in France, along with some alternate constructions found in the UK, such as vertical construction. Cases 5 and 7 were distinguishable from Cases 1 and 9 and, as seen in the fieldwork carried out in France, confirms that thermal imaging is a valid method for the French construction style, and potentially for vertical constructions also. Some further practical work would need to be carried out to fully assess if it is a valid method for the vertical constructions.

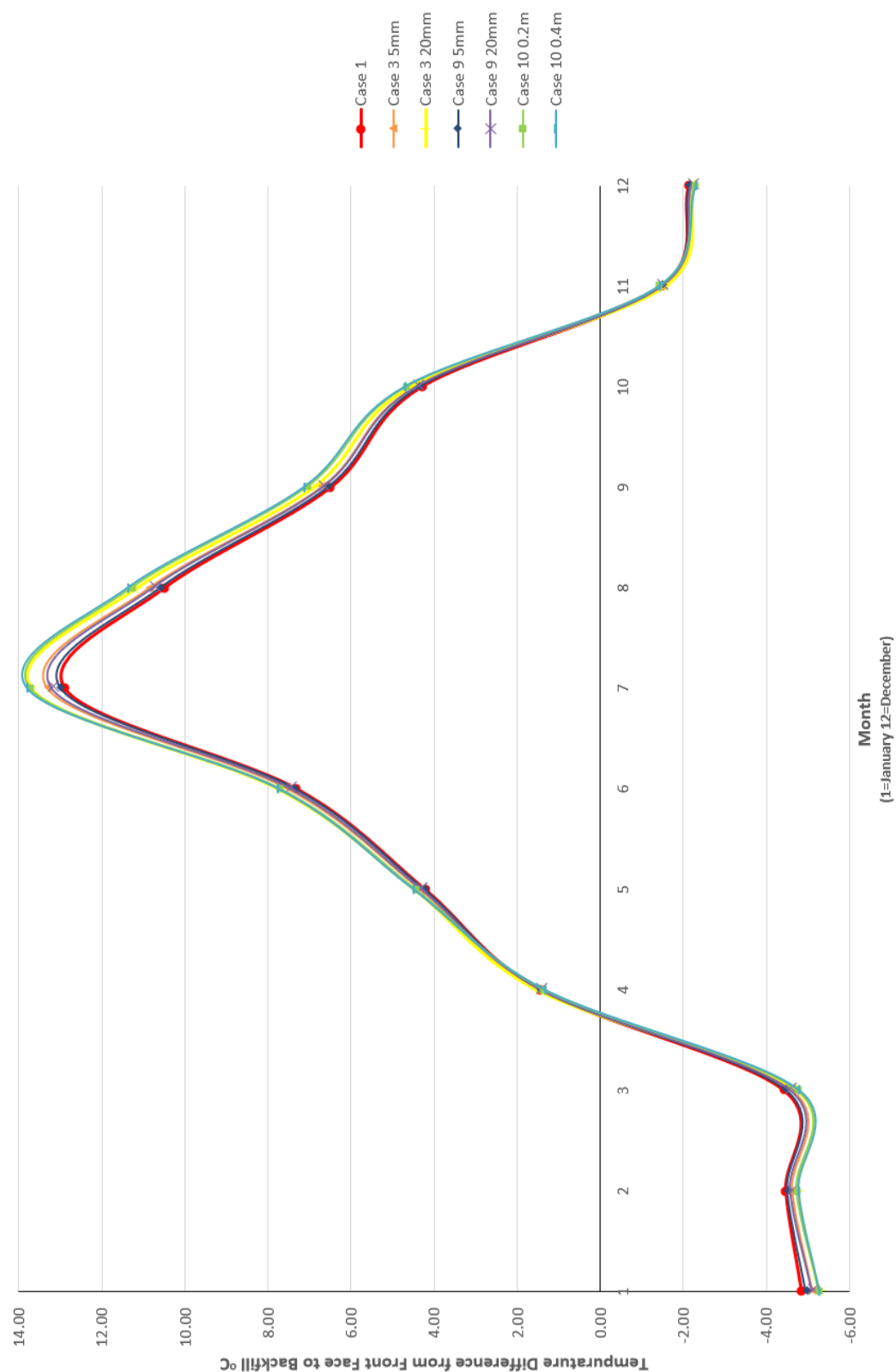


Figure 7.23: Style temperature Comparison over 1 year.

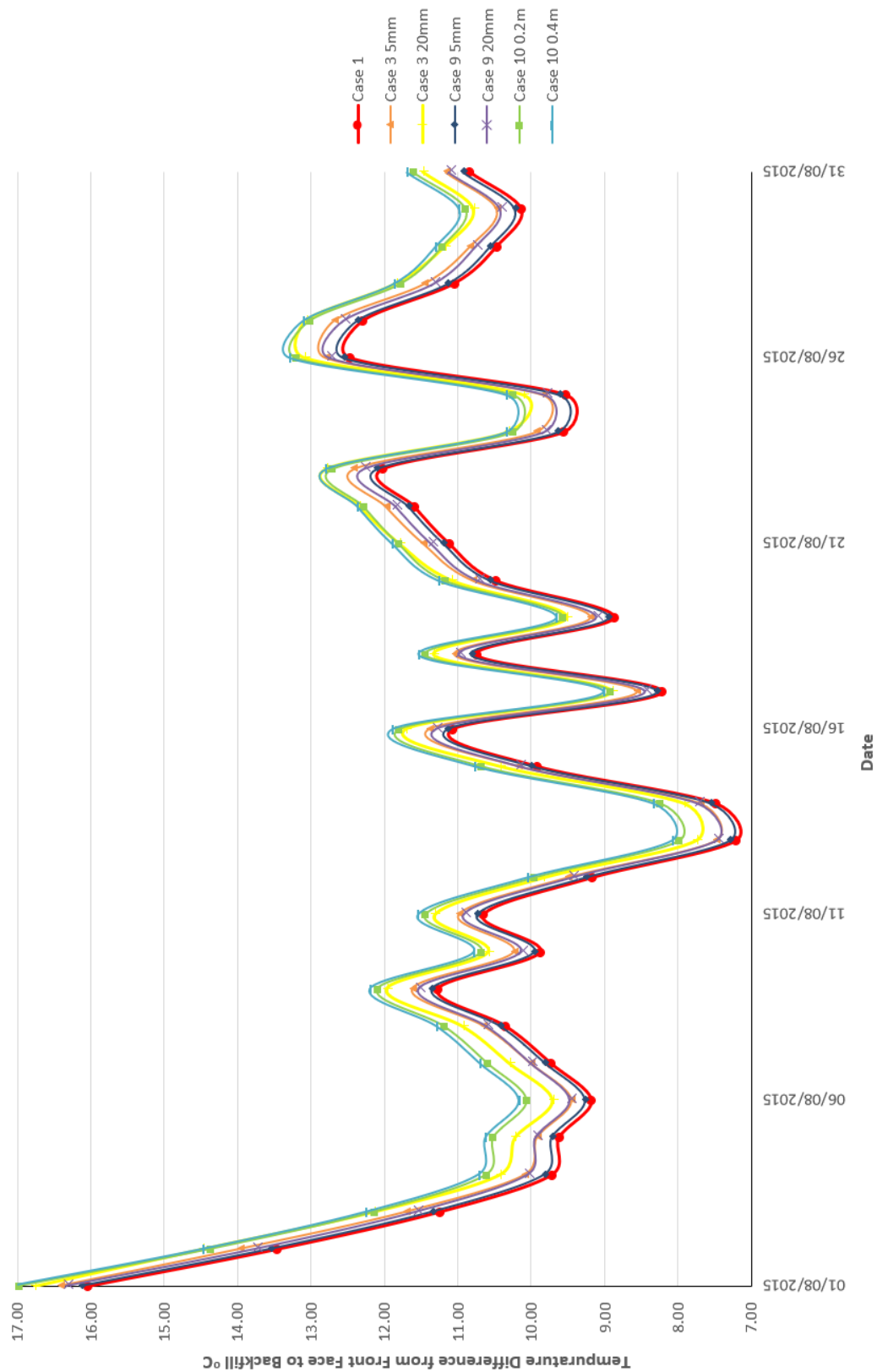


Figure 7.24: Temperature Plot for August, showing Case 1 typically coolest.



Figure 7.25: Temperature Plot for December, showing Case 1 typically warmest.

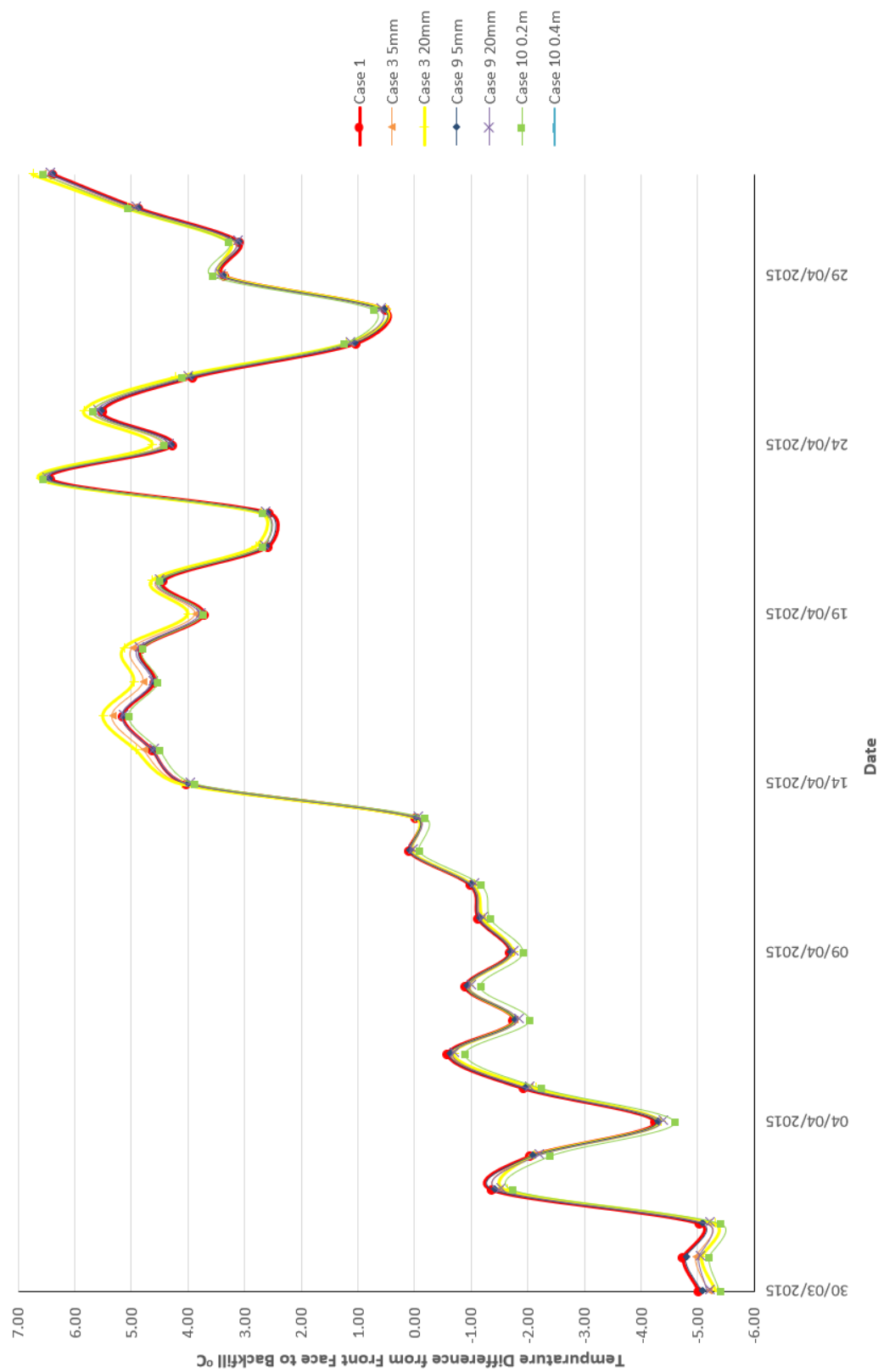
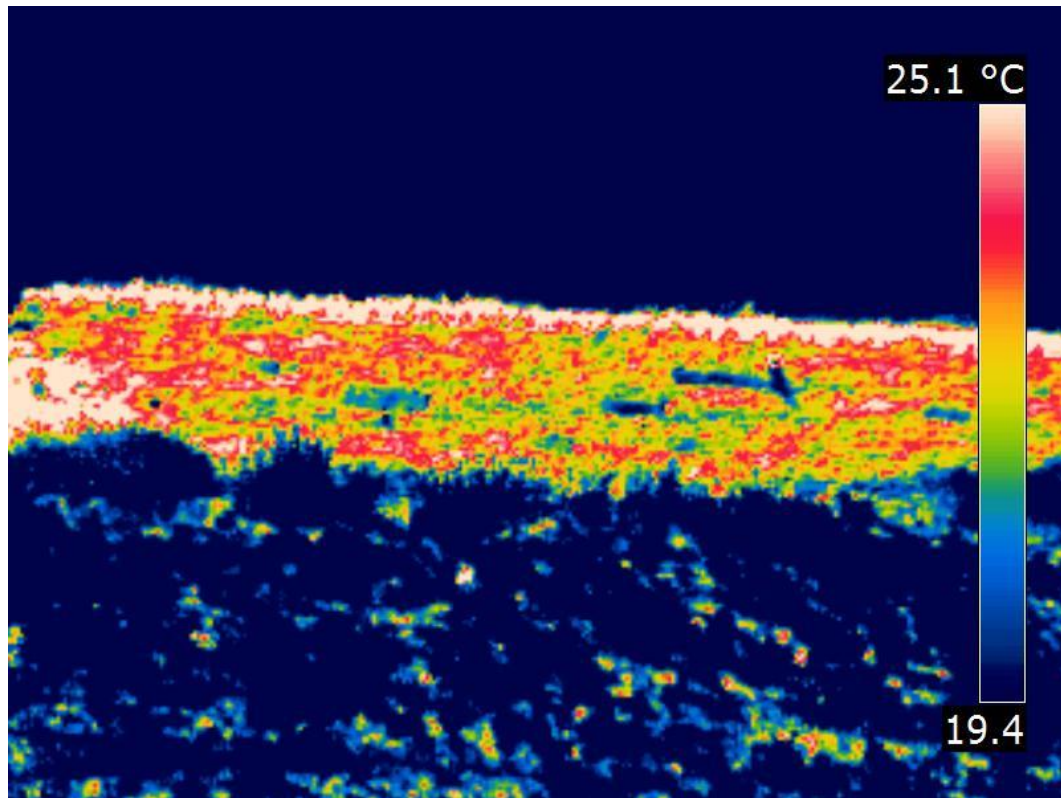


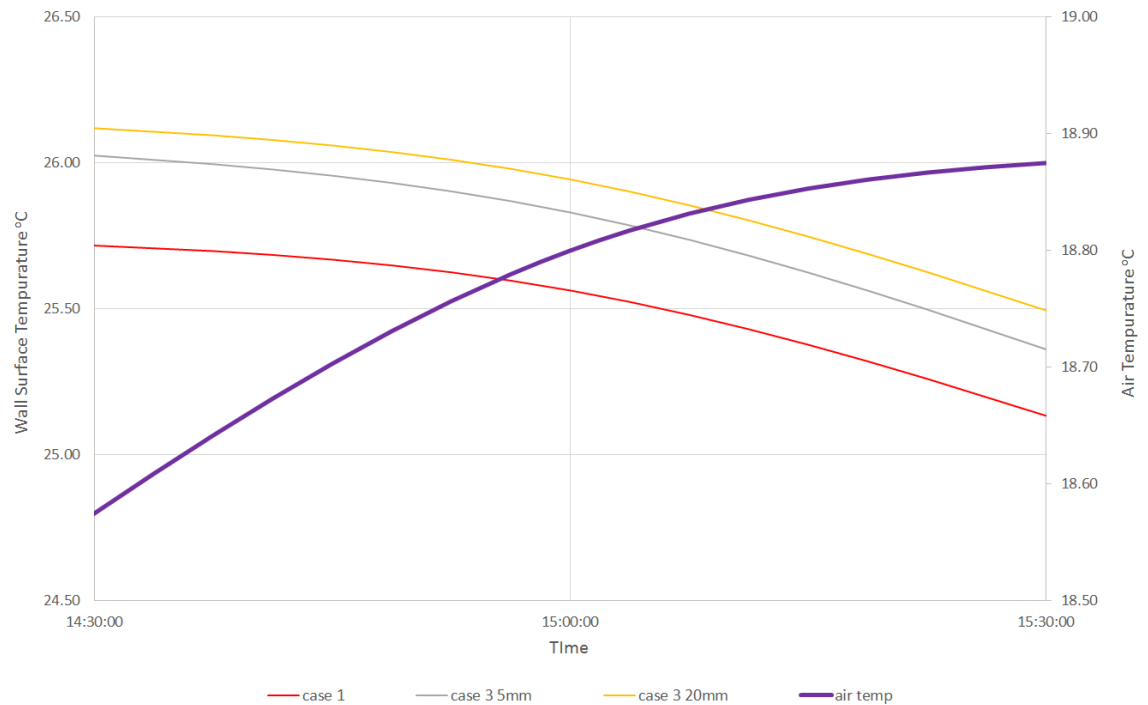
Figure 7.26: Temperature Plot for April with Case 1, Case 3 20mm and Case 10 0.4m highlighted, showing transition period.

7.4.2 Comparison to Northleach

To verify the validity of the model, it was compared to the thermal images taken at Northleach over the 6th and 7th June 2013. Here definite through stones were easily seen at the surface and were obvious when using thermal imaging. From these images it was easy to compare the through stone readings to those given by the thermal simulations, as well as the standard construction of two faces with a rubble fill between, for the times the images were taken. Figures 7.27-34 show the comparison between the thermal images taken and the thermal simulations.

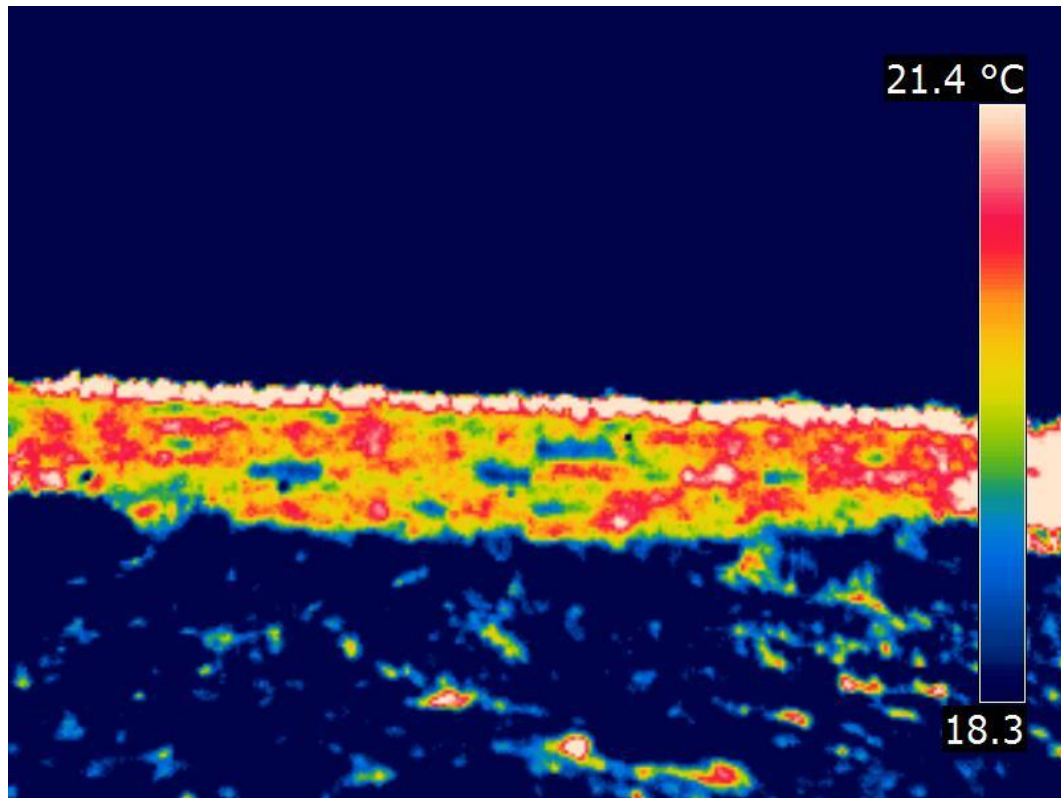


a) Thermal Image

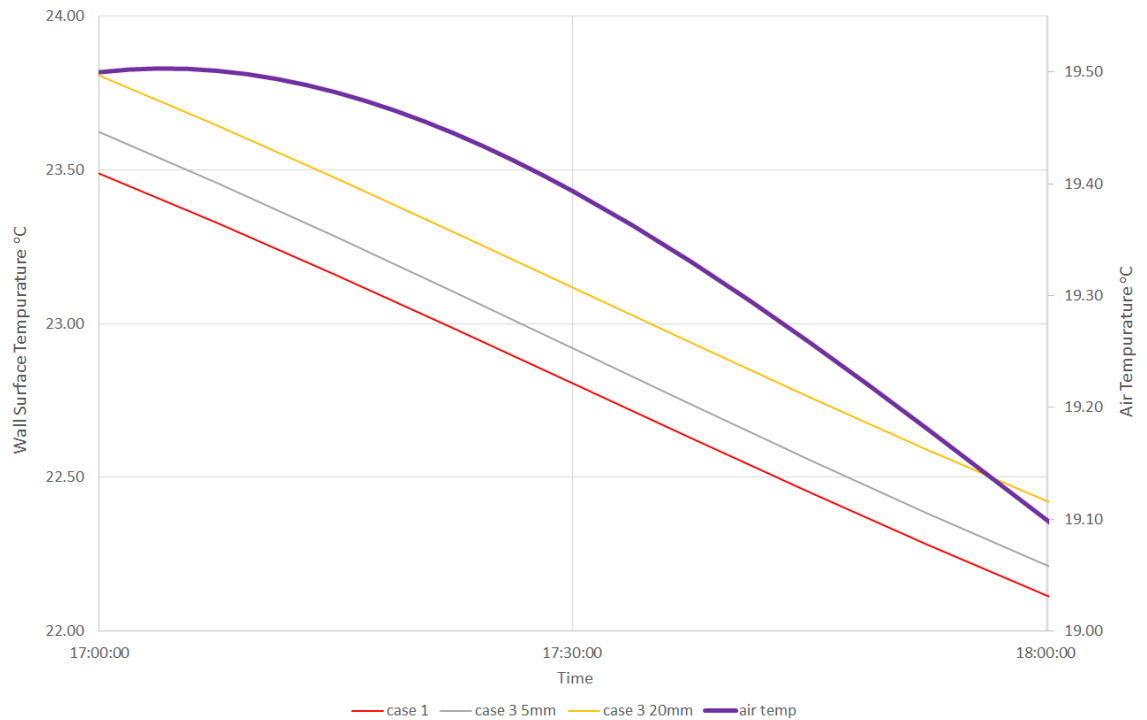


b) Thermal Simulation

Figure 7.27: Northleach Thermal Image and Simulation Comparison: 15:00 6.07.2013

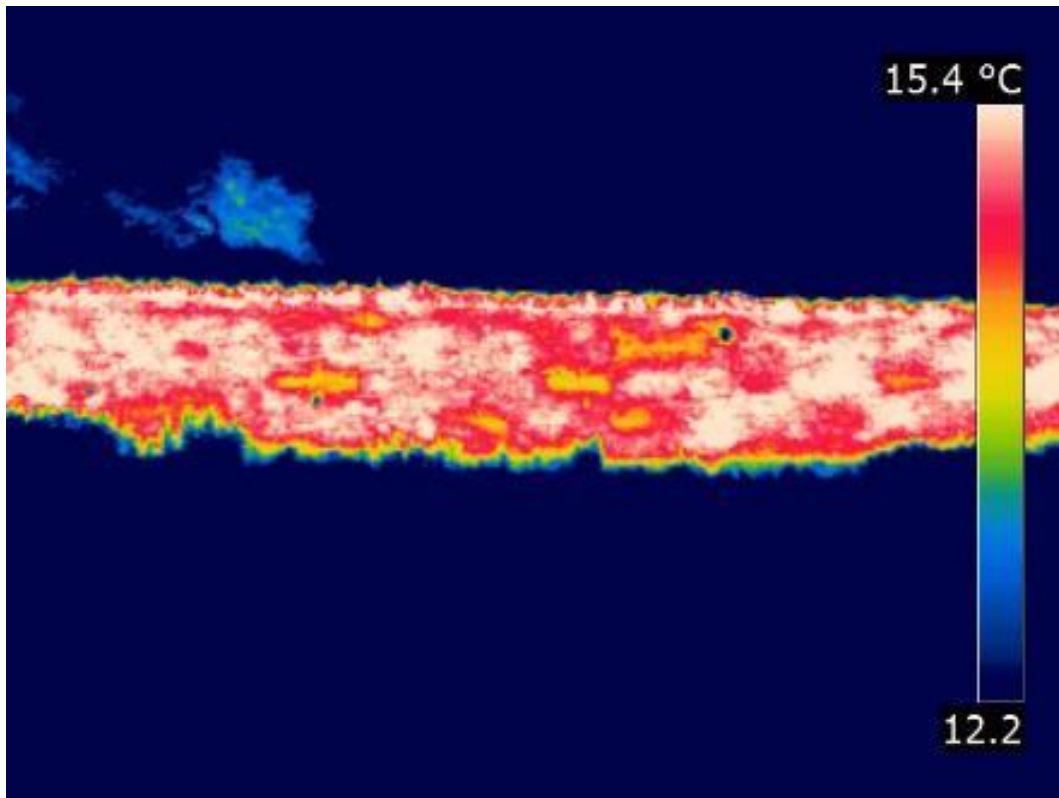


a) Thermal Image

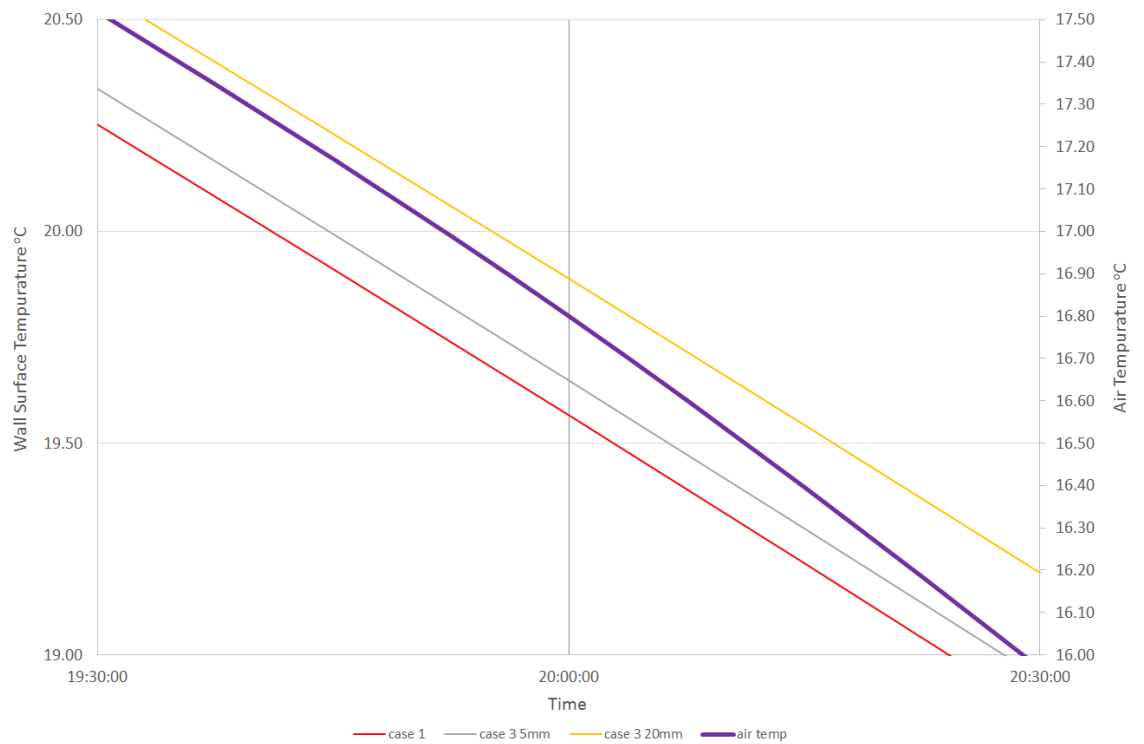


b) Thermal Simulation

Figure 7.28: Northleach Thermal Image and Simulation Comparison: 17:30 6.07.2013

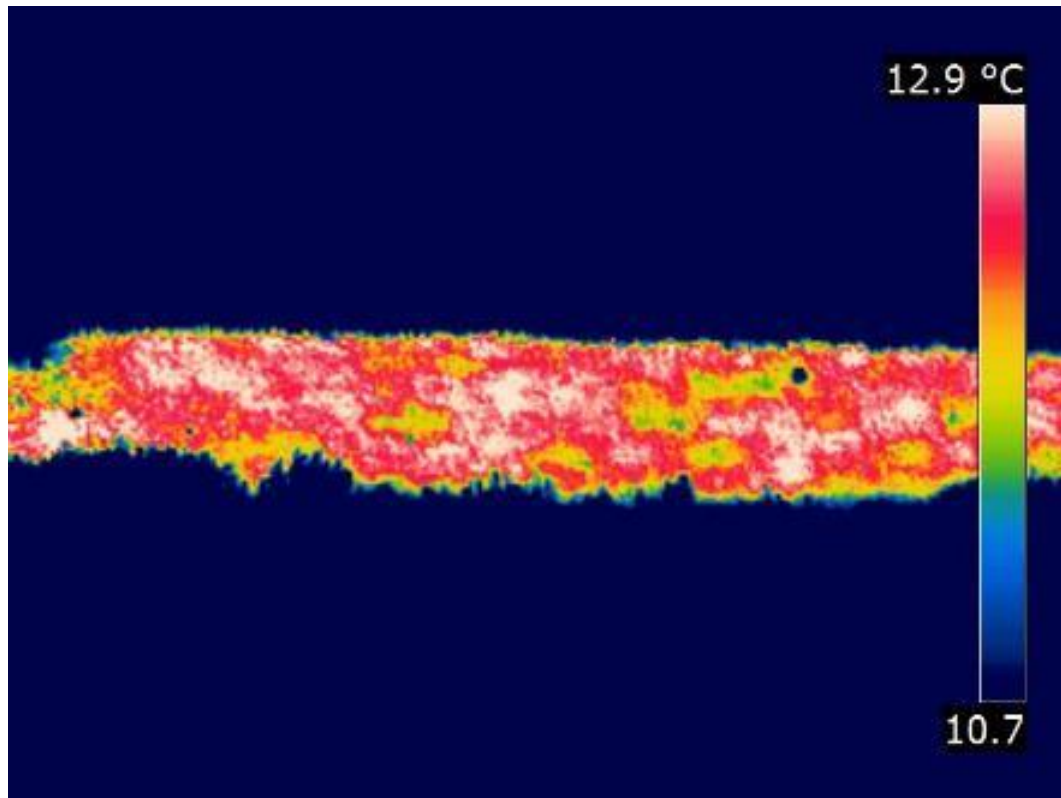


a) Thermal Image

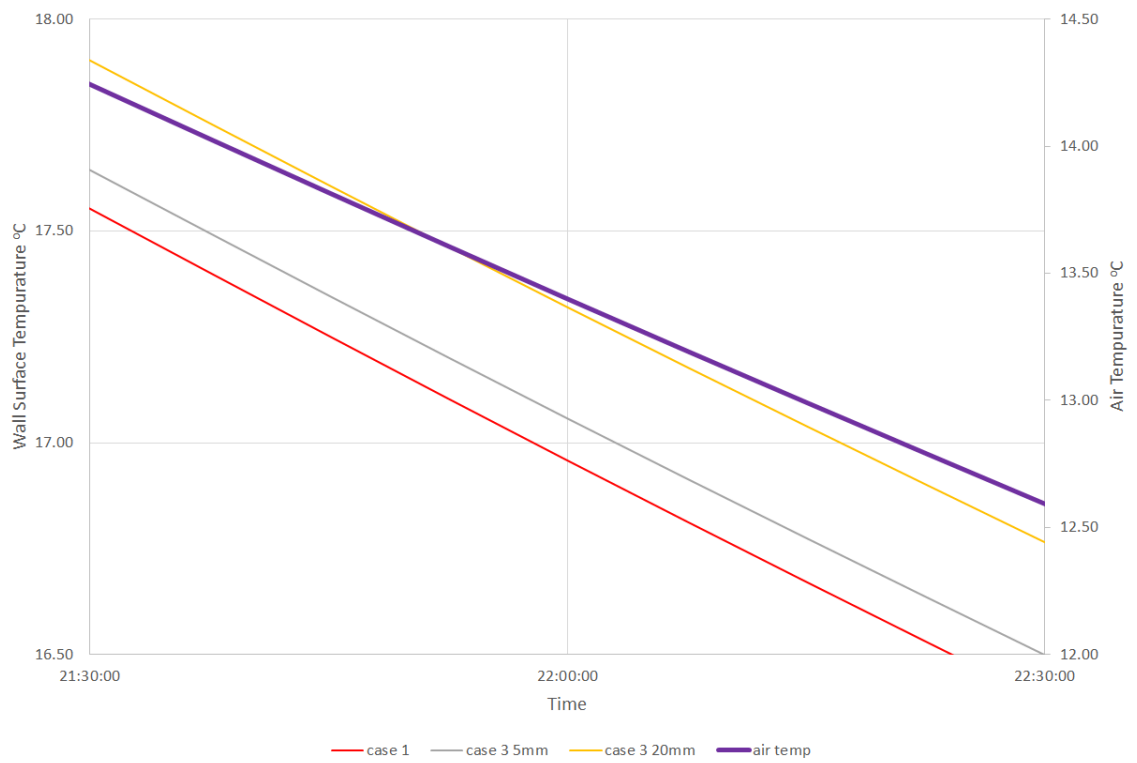


b) Thermal Simulation

Figure 7.29: Northleach Thermal Image and Simulation Comparison: 20:00 6.07.2013

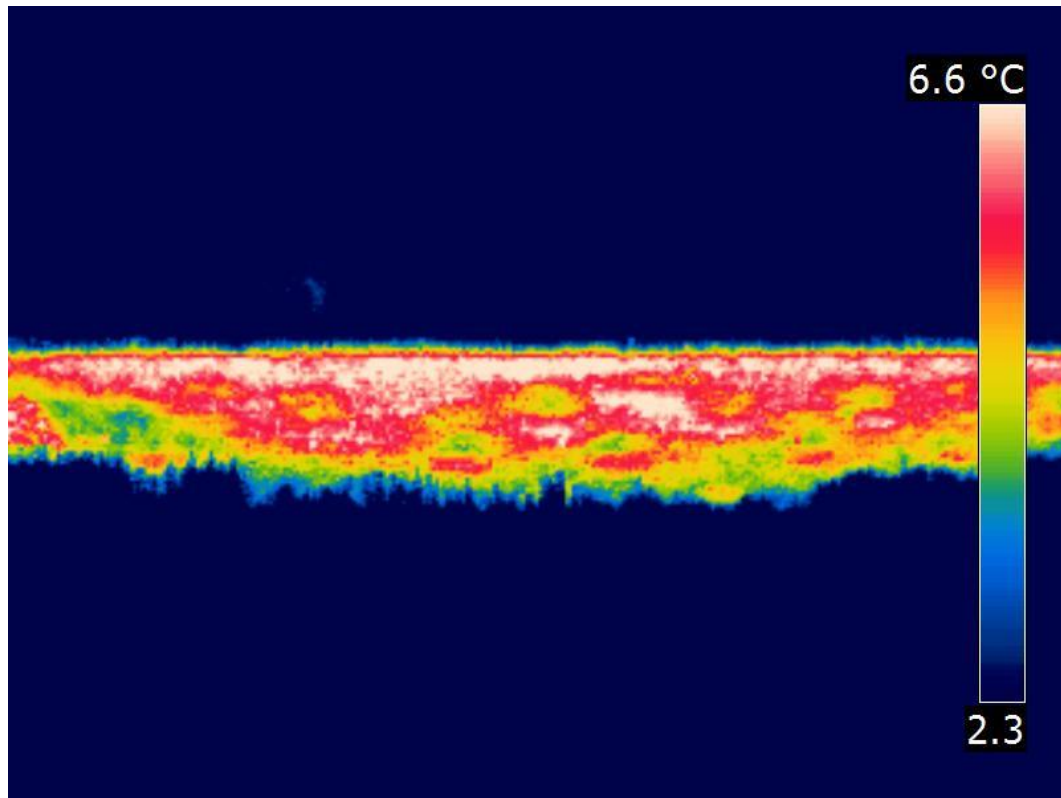


a) Thermal Image

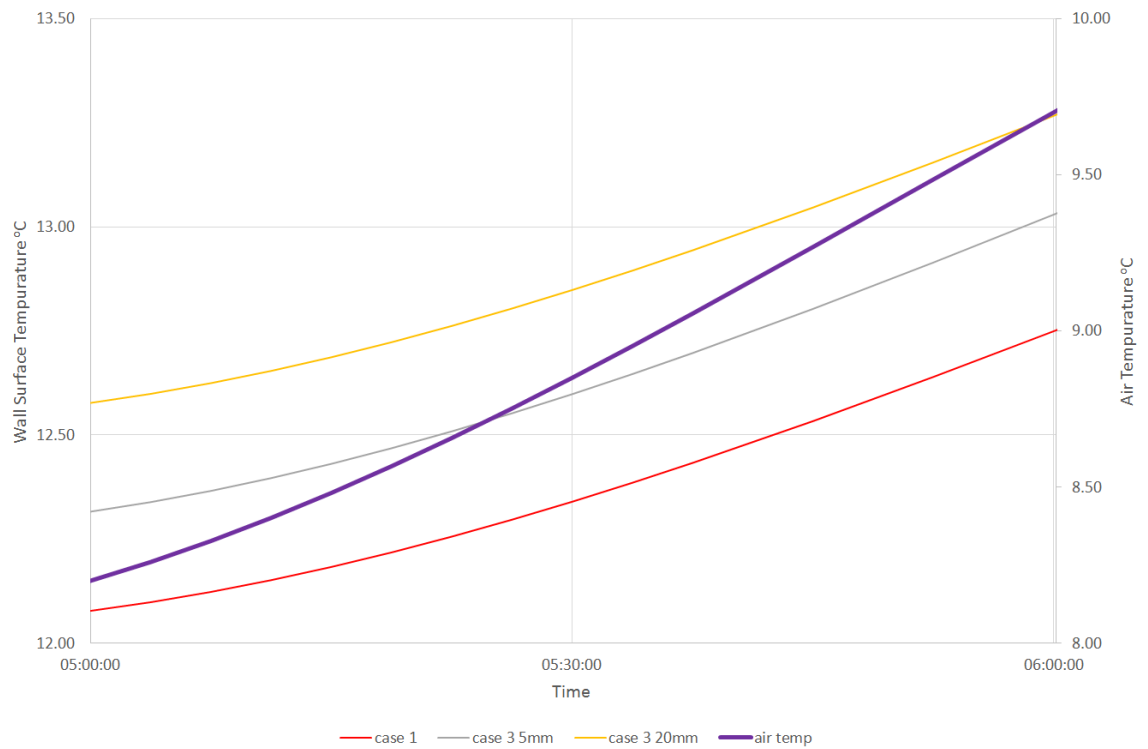


b) Thermal Simulation

Figure 7.30: Northleach Thermal Image and Simulation Comparison: 22:00 6.07.2013

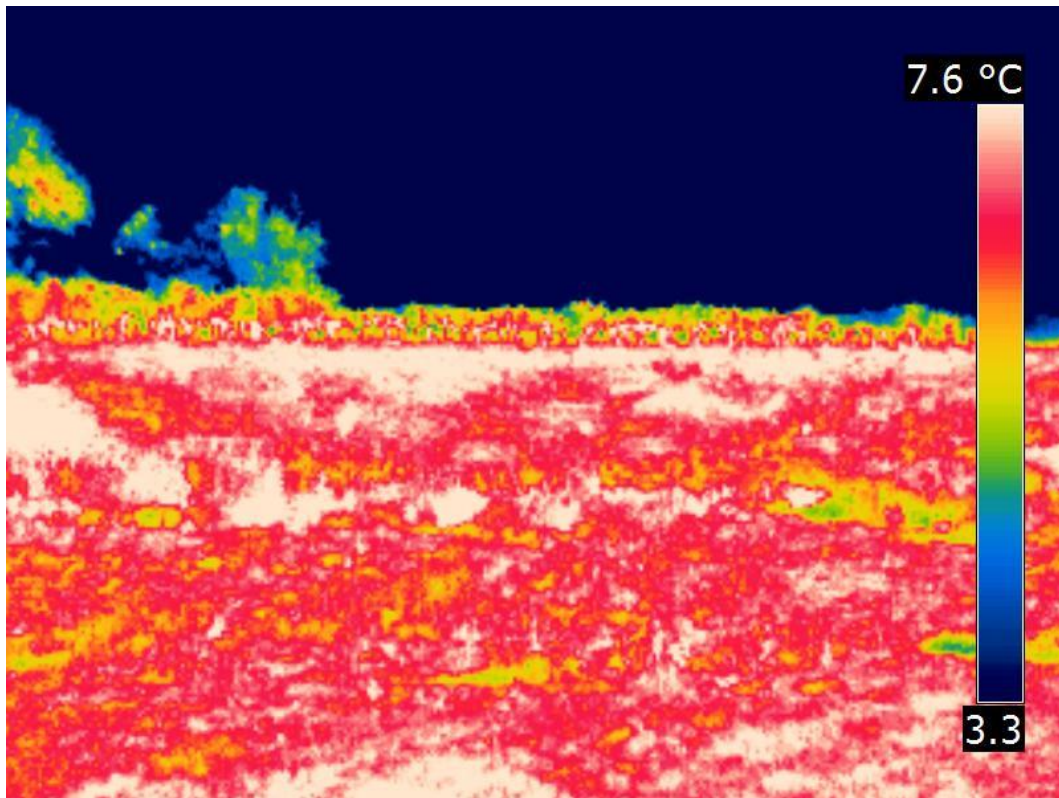


a) Thermal Image

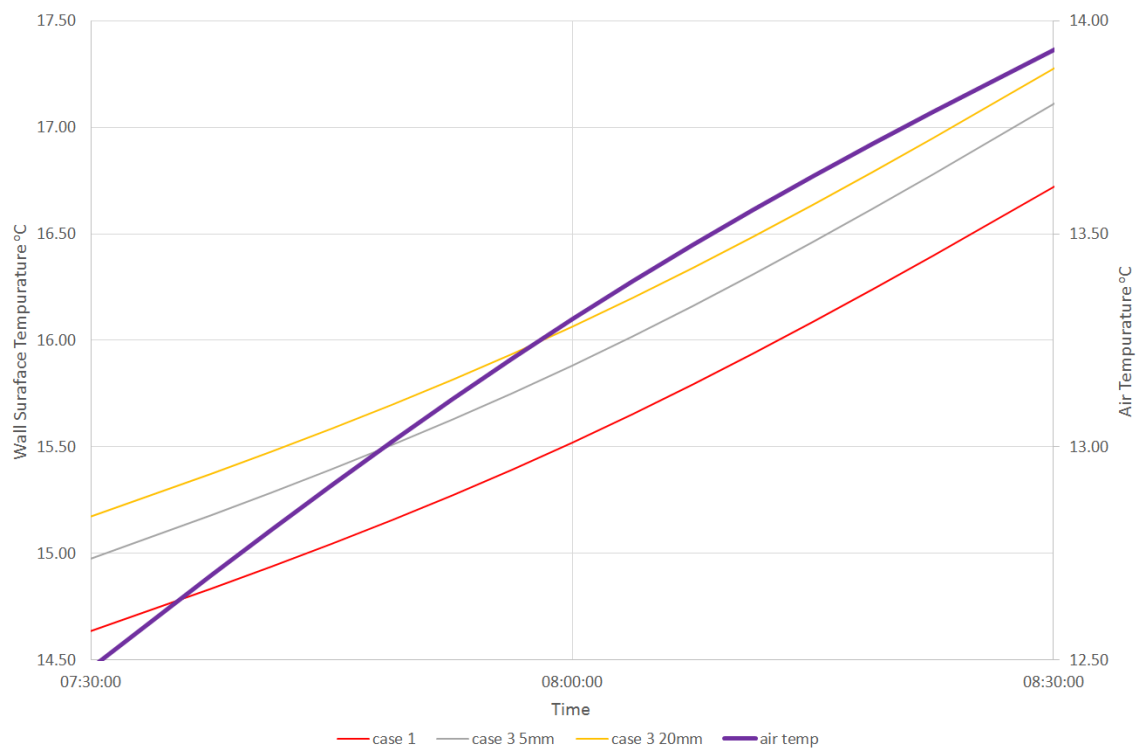


b) Thermal Simulation

Figure 7.31: Northleach thermal Image and Simulation Comparison: 05:30 7.07.2013

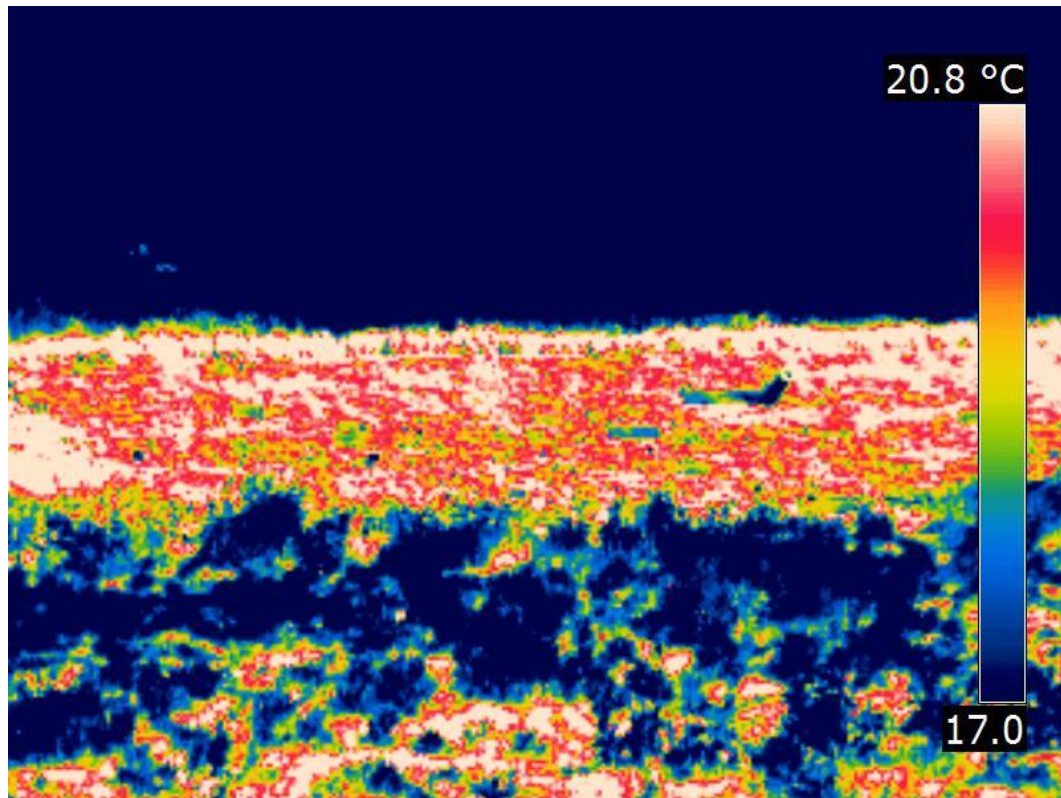


a) Thermal Image

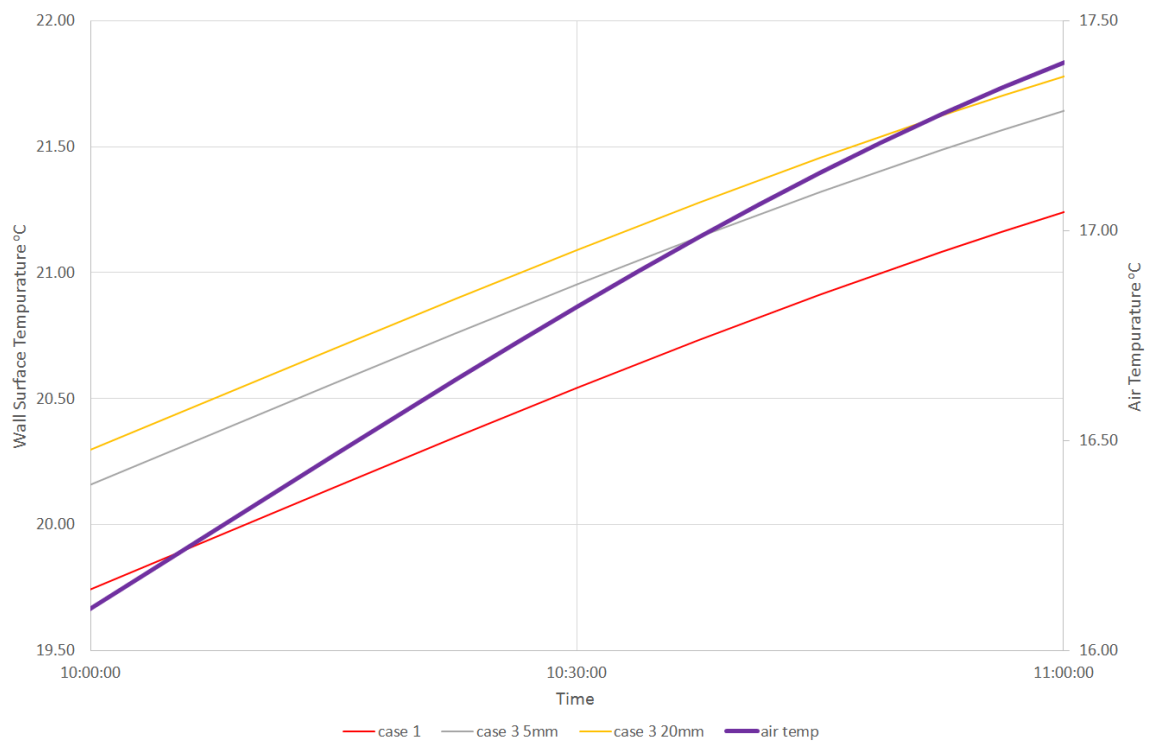


b) Thermal Simulation

Figure 7.32: Northleach Thermal Image and Simulation Comparison: 08:00 7.07.2013

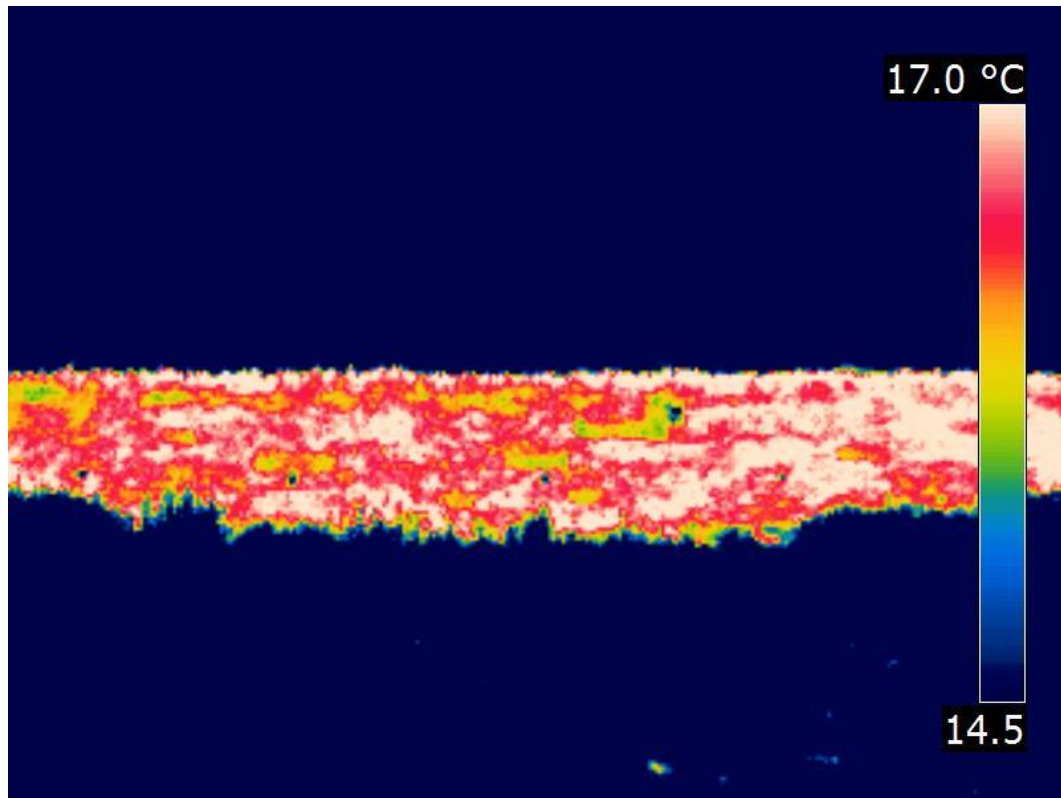


a) Thermal Image

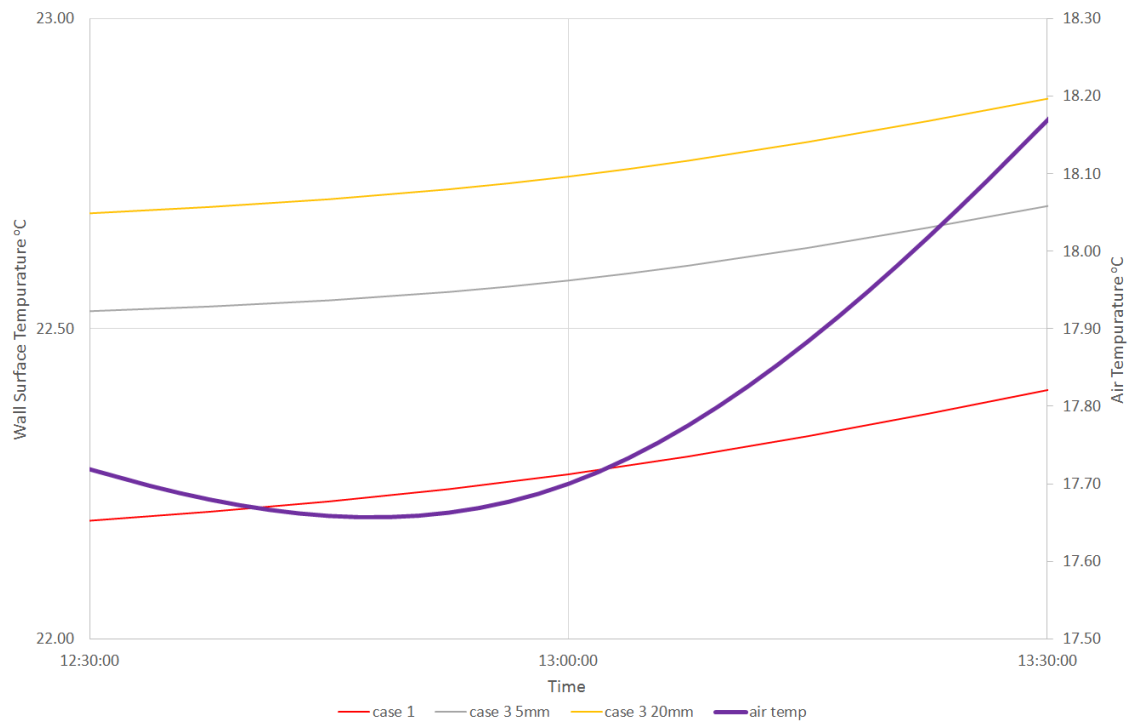


b) Thermal Simulation

Figure 7.33: Northleach Thermal Image and Simulation Comparison: 10:30 7.07.2013



a) Thermal Image



b) Thermal Simulation

Figure 7.34: Northleach Thermal Image and Simulation Comparison: 13:00 7.07.2013

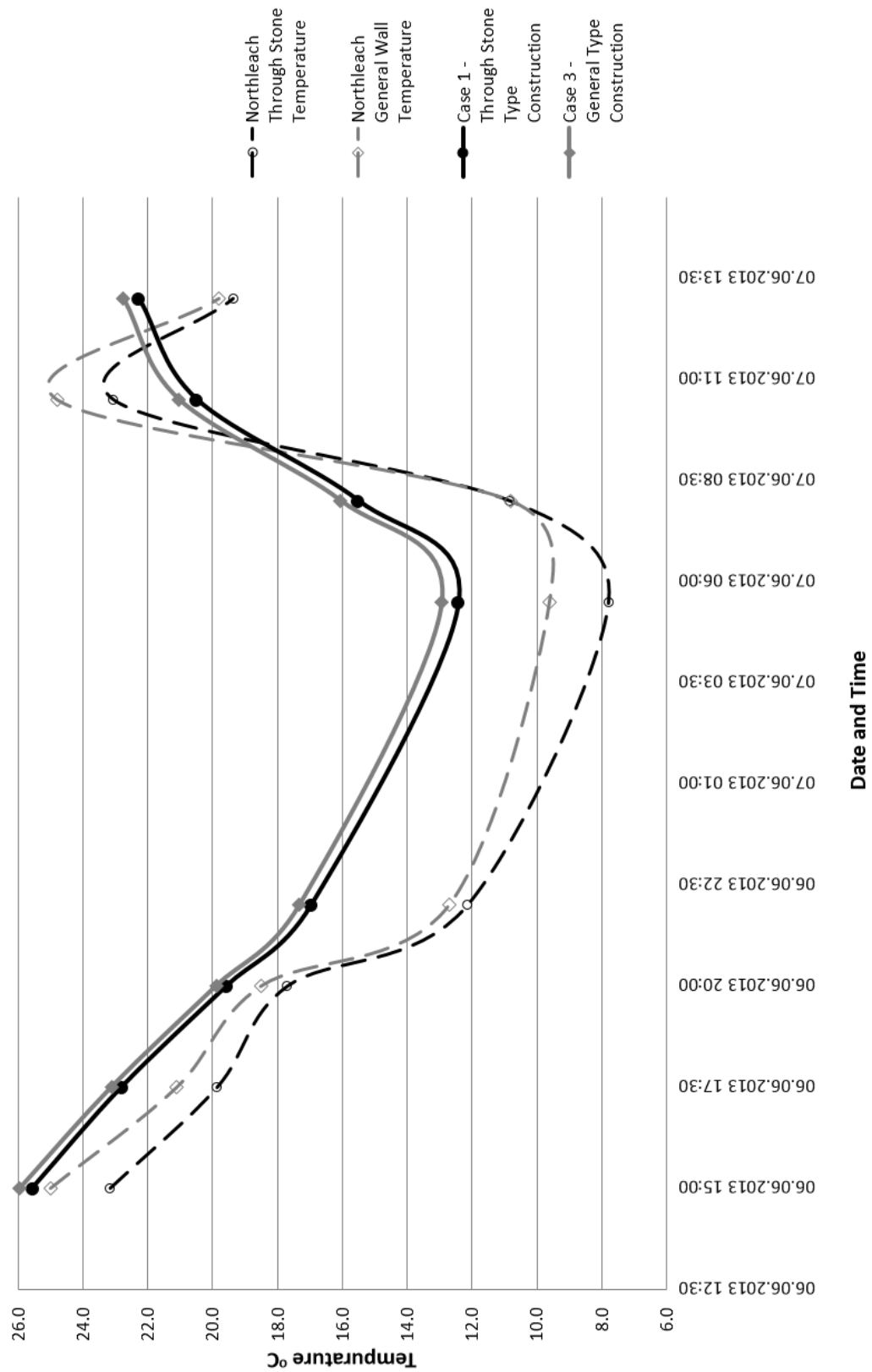


Figure 7.35: Temperature Comparison between Through type construction and General Construction for Thermal Simulations.

When comparing the thermal image results to those from the thermal simulations using Figure 7.3 and 7.35 it can be seen that both follow similar temperature trends throughout the day with the exception of the 13:00 reading from thermal imaging, which drops off from the overall trend; the potential reasons for this have been discussed previously. It can also be seen that typically the larger temperature differences between the through stone and general constructions are seen around the same periods: 05:30hrs and 10:30hrs. The thermal imaging also showed a significant difference at 15:00hrs which cannot be seen in the thermal simulations, which show a relatively constant temperature difference from 15:00hrs to 22:00hrs. The variation in the thermal imaging may be due a number of effects, potentially reflecting the local weather conditions from the previous 24 hours.

It can also be seen that the thermal simulations consistently predicted temperatures higher than that seen in the images; also, the temperature differences between the two constructions are significantly less for the thermal simulations, although similar trends were followed. In thermal modelling it is a known phenomenon that the predicted temperatures differ from actual data. This could be related to how the thermal program reads and uses the data provided or due to effects of environmental variables that do not appear in a weather file. The small variation in the location of the weather file to the actual location could also have an effect on the result (CIBSE, 2015). The weather file used also lacked data for direct solar radiation, as the equipment to record this is expensive and often not required for the purposes for which certain organisations collect weather data. This direct thermal radiation has a significant impact on surface temperatures. The thermal properties of the surfaces imaged were not entered into the camera, which would give more accurate actual temperature images; however, we are interested in the differences in temperature, which will only be affected by local variations in the thermal properties. However, the standard thermal properties typically found within the camera settings are close to that of limestone, meaning it is unlikely to have had a significant effect. The reduced temperature differences in the thermal simulations are likely to be caused by the nature of the simulations. The simulations are all 1D simulations simply looking at effects from a back to front face of infinite width and height. In reality the temperature of the stones is determined by effects from stones on all sides of the one under consideration, which can partially be seen in some of the thermal images as there is no clear temperature boundary at the stone edge. Due to the

lack of boundaries particularly in the horizontal plane, the effects of stone size are not seen as clearly in the simulations as they are in the thermal imaging. In the simulations all construction types are simulated as the same width for the full section, when in reality the through stones seen in the Northleach wall were significantly wider than those of the general construction around it allowing them to have a greater overall thermal capacity. In general you would also expect a thorough type stone to have nominally a similar cross sectional area throughout the width of the wall, whereas other stones may taper away from the face and be more triangular in plan, which would also affect their overall thermal capacity. The simulations are also carried out to a wall of nominal thickness, similar to that known to be constructed at Northleach, with an assumed constant temperature to the rear of the wall to mimic the constant temperature of the backfill. Where material properties for the Northleach wall were also unknown the properties available from WUFI were used. The assumptions on backfill temperature and material properties are all unlikely to correspond to the actual properties of the Northleach wall which were unable to be ascertained. These effects combined with the effects of the 1D modelling are all likely to contribute to the reduced differences seen.

However, the general trends seen between the Northleach thermal imaging and simulations appear to correlate, suggesting that by using simulations we can gain a better idea of when thermal imaging may be best to gain a better understanding of a wall's structure.

7.5 Conclusions

Thermal studies have shown that thermal imaging can be a useful tool in ascertaining information about existing drystone wall construction in a non-invasive manner, which in turn can be used to help form a reasonable assessment of the wall. Dependant on the time of year, or time of day, certain features such as through stones appear either warmer or cooler than the surrounding wall construction; thermal simulations also suggest areas of voiding behind the wall may also easily be seen. When compared to visual images of the same wall section it is possible to highlight areas or even individual stones that are of interest. When combined with the standard visual inspections carried

out on these walls it can help provide a greater understanding and therefore a better assessment.

From the thermal simulations it may be suggested that thermal imaging is best used at the times of year when season temperatures are steady, i.e. summer and winter, and is not as useful during spring and autumn during the seasonal temperature changes, when the air temperatures may be similar to the temperature of the backfill. However, during these seasonal changes some variations can still be seen between the through stone type constructions and the typical face and fill construction, typically found within the UK. During these times it is less clear as to which will show warmest or coolest so more care may need to be taken visually to identify the features. It may also be that during these transition periods the temperature differences are not easily detected using thermal imaging.

Simulations using WUFI were carried out to determine whether simplified 1D modelling could accurately model the behaviour of drystone walls. By the nature of the model only front to back thermal behaviour could be modelled across a single stone configuration. In reality any one stone will also be influenced by those around it, the gaps between them and the air flow in these gaps. The wall is also affected by the backfill and solar effects at the front face. For the purposes of this study it enabled direct comparisons between styles to be made as well to enable trends to be seen when compared to thermal images of walls. Further study with the use of 2D simulation would enable simulation of a wall section to investigate the effects of the influence of varying construction styles on one another and may provide results closer to that seen in the images. More accurate modelling of backfill properties would also be useful to investigate in order to gain more accurate results.

Regarding the time of day, both the field studies carried out as well as the thermal simulations suggest that most times of day will show some variations in temperature between the styles, but that the best times of day occur when there has been a period of relatively stable air temperature or period of direct sunlight on the wall. However, if used during a period of direct sunlight, consideration of the variations in the stone face angles is necessary, as this could affect the results seen at that time, as seen in Figure 7.19. The field work and thermal simulations also show that thermal imaging is suitable for walls in any orientation including north facing walls, which respond in a similar

manner to the walls that have direct sunlight on them but respond mainly to the air temperatures.

Overall it can be said that for any wall orientation thermal imaging has the potential to provide some information about the wall construction, and any potential problems, at most times of the day and year. Better results may be gained by taking images after a period of sustained seasonal air temperatures, that are not similar to the expected backfill temperatures, and during a time of day when the effects of the daily temperature changes and effects of direct sunlight are at their greatest or least effect.

This study does not look directly at the effects of water behind a drystone wall as they are typically considered to be free draining, and so water build up should not occur. However, the presence of water will likely affect the temperatures of the backfill, and as such a localised build-up of water would cause localised effects on the temperature at the wall face. Images taken at Northleach suggest this from a localised drop in surface temperature between two areas of vegetation growth, which in themselves may suggest the presence of water. This is further backed up from the study by Washer et al. which showed using polystyrene blocks that areas with differing thermal properties can be identified behind the wall face using thermal imaging. If there is water build up behind a wall, a visual inspection would also give clues to this, e.g. water weeping through the wall, vegetation growth, staining of the wall face etc. There may also be evidence of the drainage paths becoming blocked, either by grouting of the wall face or by soil movements through the wall, which in themselves are likely to be caused by water movements.

Thermal imaging in itself will not give a definitive answer to the potential problems within a wall, or the wall construction itself. The field work showed that depending on shape of individual stones, often determined by stone type and its workability, along with the stone's colour, and orientation variations, potentially false readings could be produced. However, when used in conjunction with the detailed visual inspections and the visual images currently carried out, it can provide additional information and greater insight into the wall and help see behind the wall face.

Chapter 8

Discussion

8.1 Walling styles and Assessment

Through the studies carried out it can be seen that there are a wide range of walling styles to be found throughout the UK and France. This is so even within the areas sampled, which represent a small proportion of the total number of walls, and distinct walling areas.

Through the study of these walls it can be seen that walling practices stem from years of construction with the locally available materials. These practices have grown to optimise the use of the properties of the available stone and provide mechanisms which aid the stability of the retaining walls. For example, in Cornwall it was seen that slates, which have typically lower angles of friction, are constructed vertically; they are well packed and often wedged, to produce a compression stress along the length of the wall to help resist the forces on it and increase ductility. These stones were often narrow in comparison to their height, or of smaller size with rough almost knife edge ends to the stone. This vertical style was seen both in Cornish banks and domestic walls, as well as in more significant coastal structures. Where used in coastal structures, this vertical construction is also likely to aid water shedding and reduce the uplift forces from waves on the individual stones.

Conversely in Wales where the slate type walls were used as embankment structures these walls were seen to be constructed horizontally. The stones seen were also of much greater size and it may have been that walls were constructed in this way as a

matter of practicality, since to lift and place a stone mechanically it is much easier to do so horizontally. The lower friction on the flat surfaces of the stone is compensated for by a greater width of wall, so there is increased loading on the top of the wall as well as on the fill behind it, because the rail loads are at least in part actually on the wall itself. This results in additional compression within the wall, which helps to resist the shearing pressures.

In the Cotswolds, where the limestone is known to be prone to degradation through water ingress, the outer face of the wall is constructed with the stones sloping downwards out of the wall face to aid water shedding, and prevent water running into the heart of the wall. This goes against all published good practise; however, due to the high frictional properties of the limestone and the double skinned construction, which means the rear of the wall can still be constructed with the stone sloping into the backfill, these walls are able to withstand the loads upon them and remain stable. However, even with these precautions a high percentage of the material within the wall is still found to be unusable should reconstruction be required.

In France it was found that wallers place all their stone sloping into the backfill, as this not only aids stability but means water is quickly able to travel to the backfill and disperse from the wall. Although there is subtle reasoning for the use of a certain style or variation it can typically be said that: where stones are workable and have high frictional properties or are of significant size but may have lower frictional properties horizontal construction will be most common; where stone has lower frictional properties and may be less amenable to being worked vertical construction will be most common; where stone is not workable but is of a size to be able to resist loading or have higher frictional properties random construction will be most common. Cross overs between the styles are also inevitable where stones do not conform to one of the stated groups.

It is also likely that the general retaining wall styles come from the predominant use of walls within an area. In England the majority of drystone walls are found as field boundaries, traditionally made using stone from field clearance. In order to construct these walls and make them free standing, and taking into account the nature of the majority of the stone within the UK, these walls are constructed using two outer skins with through stones to tie them together, and a well packed fill of smaller stones

between the outer skins. This tradition has then found its way into retaining wall structures, particularly for more significant structures where we often still find the double face arrangement with the rubble fill and through stones, though these may well now extend into the backfill.

In the area of the South of France studied, the main walling construction here is retaining walls. Here we find the walls, while still mainly horizontal, are constructed using mainly larger stones which interlock and are continuous throughout the wall. This forms a more solid structure; and the smaller stones and cut-offs are often placed behind the wall to aid drainage. While techniques similar to this are acknowledged within the UK, it appears to be far less common and is mainly used for small structures in more domestic situations. Many wallers say they place extra stone not suitable for walling immediately behind the wall to improve drainage, as a way of making good use of it.

Through the examples of existing walls it can be seen that both methods are well able to provide the function they are constructed for, however with similar materials the two differing styles have grown independently. It is not surprising that in the UK the construction techniques known to work for the free-standing walls have been adapted for the retaining walls, as it is a method that craftsmen are happy using and are able to construct easily.

Many of these walls are under the care of local authorities, along local highway infrastructure. As part of the study Gloucester and Cornwall county council were consulted to ascertain how they deal with these structures, how they are recorded and what information would make assessment easier. Gloucester was found to have a reactive mechanism to the walls in its care, only becoming aware of a structure once an issue had been raised by a member of the public. Cornwall were found to be more proactive, actively recording walls in their care so that if issues arose they had a point of reference. In both cases the recording and assessment of drystone was the same as for standard masonry structures, under the general category of retaining walls.

Also, in both cases the assessment of these structures is typically based on a visual inspection, both of the wall and of the road above or below if appropriate. From this visual assessment a judgement is made regarding the walls condition and the way

forward. Typically unless actual collapse has occurred or significant deformations/problems are visible, the normal strategy is continued inspection. However, for these inspections to be useful prior knowledge of drystone is essential, both to the mechanisms involved within them and the local variations that may be found.

Through the previous full scale studies carried out, and with knowledge gained through talking to wallers who deal with these structures every day, we know that the visual quality of the wall may not be a true representation of the walls capabilities, in both Colas' (2012) and Mundell's (2009) experiments it was found that the walls deemed to be constructed of a poorer quality, and visually were of poorer quality, performed nearly as well as, if not better, than the walls deemed to be of better quality with a high finish to them. Also, these walls have a large capacity to move and deform into the classic bulge shape, while still being stable under their current loading. Also, there is a distinct possibility that if compared to the text book way of walling, walls may be automatically deemed as unfit, and potentially to be unnecessarily replaced. This is particularly so if the subtleties of local variations are not properly understood, such as the Cotswold walls in which stone slope forward out of the wall,

However, it is commonly recognised around the walling world that certain features are known to aid a wall and others are detrimental, such as the presence of through stones or larger stones penetrating into the wall to tie the wall together, so that it acts as one. It is also known that voiding behind the wall is likely to be detrimental and can indicate other issues. Another problem councils have in assessing walls is identifying these features, which may not be apparent at the wall face. Knowing the presence or lack thereof is likely to help significantly with any judgement to be made concerning a wall.

Through field work carried out, and simple thermal modelling, it has been shown that thermal imaging of these walls at certain times of day can help pick out these features, which may not be immediately obvious at the wall face. For example, thermal imaging of a wall in France revealed that some stones at the face which were comparatively small compared with those around them penetrated further into the wall and provided the through stone function.

Measurements of the stone angles of horizontal stones at the wall face can be compared to the frictional properties of the stone, and a judgment made regarding its capabilities to resist loading. For example, if stones slope back into the wall the forces on the rear of the wall need to overcome this angle as well as the friction angle on the stone surfaces. However, if through wall movement or local building variations the stones are flat or slope away from the wall face, a lesser force will be required to overcome friction; so, where stone has lower frictional strength, stone consistently sloping out of the wall face is likely to be significantly detrimental to the wall stability.

During assessment it is also important to look for the modifications that occur over the years. One of the most common alterations carried out in good faith is to mortar or grout the front face of the wall, or the wall as a whole. Whilst this is carried out with the aim of stabilising the wall, it is also detrimental to a drystone wall's most advantageous feature, in that it prevents the free flow of water through the wall. Being naturally free draining drystone walls are not traditionally constructed with additional allowances for drainage such as weep holes. Placing mortar in the walls prevents the free flow of water through the wall and therefore allows water pressures to build up behind the wall, leading to additional pressures which may cause failure. Mortaring also prevents the natural flexure of the walls and the redistribution of loads, which again instead of aiding the wall may contribute to its demise.

In addition to the above methods, geophysical methods were also examined, and experiment were carried out using Ground Penetrating Radar. This method was chosen to investigate as it requires no shock waves to be applied to the wall body, which seismic methods require, which could in itself lead to further damage to a marginally stable wall. It can also be carried out at the wall face without the need for sensors to be attached or inserted into the wall itself. It was hoped that this method could indicate the distance to the rear face of the wall, as the wall width is a critical factor in analysing its stability. It was also hoped that if through stones were substantially larger, they may also be indicated. However this method proved inconclusive, with little information gained from the results provided. Potentially this was due to the equipment available which is typically used for the locating of buried services, and uses a comparatively low frequency which has a greater penetration depth but less resolution. As such it is likely the area of interest i.e. the wall, was not in the optimum zone for the equipment. Also the multiple air/stone interfaces within a wall will cause multiple reflections and

refractions which will create a lot of noise in the return signal, making image processing difficult. This phenomenon will also be present in any other signal based method used with drystone. The use of a higher frequency unit with a lower penetration may mitigate some of these issues and would be worth further investigation.

In many ways drystone principles go against modern conventional practice, so if engineers are to assess these walls then they need to gain a good understanding of not only the general principles, but the subtleties between them. The work carried out has examined these and given theories as to how principle construction styles work, as well as providing the basis for an assessment tool that helps provide information regarding the wall behind its face. This is one of the main issues faced by engineers trying to assess these structures. Thermal imaging can easily be used within current inspection regimes as in the field it is little different to using a standard camera. It also has the potential, as part of an ongoing assessment, to pick up changes that may not otherwise be obvious. Investigating stone angle is also a simple method of gaining information regarding the general construction as part of an inspection. However, it is also important to have a knowledge of any local variations from the published good practice when assessing in a specific area, as they can go against general advice to make best use of the stone available.

8.2 Future Work

Through this study and looking at previous studies, potential for future work has arisen, both to help understand construction further as well as to aid assessment.

Almost all the current published full scale work has been carried out on horizontal construction. This is unsurprising as it is probably the most common form of construction found, and is also the particular construction style found in the areas where the full scale testing has been carried out. However to further understand walling stock as a whole it would be advantageous to carry out similar studies using the vertical and random constructions. Further testing to see how these structures behave in coastal situations would also be recommended, as vertical and random styles in particular were often found to be used in coastal defences.

Also unsurprisingly the current testing has been carried out on new build structures. While this aids the arguments for using drystone as a viable option for new structures and gives indications as to how existing structures may behave, it is likely that walls that have been in situ for a significant period of time may behave differently due to external factors that have affected the wall during its lifetime. The aging and weathering of the stones may also affect the wall, whereas current research has been carried out using new stones. Where walls are currently rebuilt they are often built from the existing stone within the wall that has been demolished or the existing stone mixed with some new stone. In practical terms it is unlikely that full scale testing of an in-situ wall will be possible, as it involves finding wall owners willing to allow this to occur as well as a number of other issues that need to be considered. However, the testing of walls constructed using stone that has come from an existing wall that has had an extended working life would go some way towards seeing how or if this affects the wall capabilities.

It is also known that a number of modifications are often made to walls, such as the mortaring of joints. It is known generally that this is not good for the walls and will prevent the movement of water through the wall. Testing of mortared walls would provide indications of how this effects the wall and if it shortens the life of the walls.

With regard to non-destructive assessment thermal imaging has proven to be of use in horizontal constructions of varying styles, as well as in some random constructions using a variety of materials. From the simulation work, it is expected that this technique will also be useful for other construction styles. Practical verification to support this would aid this technique as a wide range assessment tool. Work to further extend the thermal simulation of drystone walls with varying backfill properties and to investigate 2D and possibly 3D simulation to see if results closer to those seen in field studies would potentially enable further trends to be shown that were not highlighted in the 1D simulations.

With regard to other potential tools, further investigation of Ground Penetrating Radar (GPR) would be worthwhile. While the initial investigation carried out in this study was inconclusive this was deemed to be partly down to the equipment available.

Investigation using smaller high frequency antenna may be able to provide useful information regarding the wall as a whole, such as wall thickness, if not about the

individual stones. Knowing how thickness of the wall would make a big difference to the ability of engineers to assess these structures; currently, unless adjacent sections have collapsed, determining this is very difficult or impossible without disturbing the wall, and typically defeating the object of assessment.

Chapter 9

Conclusions

9.1 Conclusion

Through the studies carried out it can be seen that although there are the three main construction styles: Horizontal, Vertical and Random, there are a wide variety of variation within this, even within the relatively small areas surveyed. The style and these variations reflect the nature of the stone used and has developed over time to optimise the stone properties to provide the greatest resistance to applied forces. Each construction method is likely to have differing mechanism within them to optimise the stone weight and frictional properties, along with its workability.

In both France and the UK there are various publications by the walling bodies, the Dry Stone Walling Association (DSWA) in the UK and the Artisans Bâtisseurs en Pierres Sèches (ABPS)/Confédération des Bâtisseurs en Pierre Sèche (CBPS) in France, which provide guidance on good practice in construction of drystone walls and structures. While mainly focused on the horizontal construction some guidance is also found on other construction styles with the UK guidance mainly formed around field walling techniques which are then translated to retaining structures and in France guidance is mainly formed around retaining structures. Though in essence the construction styles differ between the UK and France the basic principles remain the same forming a wall which is well bonded throughout its width and into the backfill behind. These principles are also followed where construction styles other than horizontal are adopted. In horizontal construction Stones are also angled to aid water shedding from the wall face.

Through discussion with wallers and through field work, the choice of style and the intricacies within it vary to reflect both wall use and to suit the stone properties. These variations are often passed waller to waller with no real documentation e.g. in the Cotswolds it is common to place outer stone sloping down to aid water shed from the wall face as the limestones in this area are particularly prone to degradation from water, whereas typically the advice is to slope stone back into the wall to aid stability and to shed water into the backfill. The limestone in this area has sufficient frictional properties to allow this forward facing slope to be accommodated. This means when looking at these structures some degree of local knowledge is required, often the best way to gain this is to talk to wallers within an area who were found to be more than willing to pass on any information they could.

Various full scale testing carried out both in the UK and France have also shown that the wall does not visually have be as good a condition as may be expected to be able to resist loading, and that in some cases what appears to be a well-constructed wall at the face may not be as well constructed as it first appears. However good practice dictates that there are features within a well-constructed wall which will aid its stability such as through stones, and features which are known to be detrimental to its performance such as voiding and water build up. However, at the surface of the wall these features can be hard to identify. Typically, it is assumed the larger stones at the face of the wall act as through stones however through field work it was found that it is not always the case and it can be the smaller face stone that penetrate further into the wall.

Through studying the varying construction types proposals have been put forward as to how each construction type reflects the properties of the stone typically found to be constructed in these ways. The field studies also suggested that construction style may also reflect the use of the wall e.g. where used in tidal regions walls drystone walls are often seen constructed vertically, presumably to aid water shedding and reduce uplift effects on the individual stones.

Typically, within the UK many of these walls fall under the care of local councils and highways and as such the task of assessing these structures falls to them. Through discussion with Gloucester and Cornwall county councils, how these are dealt with can vary, Gloucester was found to have a much more reactive system where walls were only known about and assessed if concerns were raised by the public regarding a structure.

Cornwall on the other hand have an active programme to record walls, such that if are raised they are able to compare the current state of the wall to that previously recorded. However, in both cases, assessment relies predominately on visual inspections of the wall at the wall face. Those that assess these walls may have little prior knowledge of drystone or the mechanisms involved in their stability, and the walls are likely to be assessed in much the same way as any other bonded masonry wall. Much assessment is carried out visually with parameters that are easy to obtain being recorded, e.g. height, stone type, parapet height if present, obvious areas of distress (partial collapse or missing stone), and major deformations. Where collapse or partial collapse has occurred or significant areas of masonry are missing, often replacement is carried out using a more conventional masonry method or on occasion gabion construction. Where imminent failure is less likely often a scheme of continued visual inspection is put into place at varying intervals. Currently there do not appear to be any systems in place for identifying features such as through stones or any assessment strategies specifically for drystone construction, and assessment often relies on engineering judgement. However, from discussion with councils any tool that would help identify features within or behind the wall would be of benefit in aiding the assessment of these walls.

With this in mind thermal imaging was investigated with the aim of identifying features within a wall that could aid those assessing these structures. Thermal imaging was chosen as it can be used remotely from a wall, which where a wall is potentially unstable is advantageous. It also is relatively simple to use, with a modern camera being little different to using a normal digital camera and will not add significantly to the time taken when visiting a wall. These thermal images can then be processed using free software available with the cameras. The practical work it has also shown that this is a valid technique for picking up features within the wall along with the potential to highlight other areas of interest and variations in the tightness of constructions.

This has been compared to simple thermal modelling using WUFI a commercially available 1D thermal assessment model often used for the assessment of building skins, showing the use of 2D or 3D simulations may be better in predicting the thermal behaviour of drystone retaining structures. The study has shown that this technique is valid for all wall orientations at nearly all times of year, though whether features show warmer or cooler than the general wall construction varies depending on the time of

year, and time of day. It was also found that for the identification of features in particular through stones it is best if the wall is not imaged during the natural temperature transition periods of the day, but after the wall has either been exposed for a prolonged period of time to either the relatively cooler night air or prolonged period of heating from the sun.

From the thermal simulations along with the work carried out thermal imaging has the potential to provide information for a wide range of walling constructions. This alongside the previous full-scale studies should go a long way in helping in the assessment of drystone retaining walls. This technique can also be used as part of ongoing monitoring works to highlight any changes in the wall that may not otherwise be visible.

References

- Adcock, S., 1996, [Accessed: 21.10.2012], Stonechat-Summer 1996, Issue 10, Drystone Walling Association Wales, Available from: <https://www.box.com/shared/0lv43sfgq0>
- Arias. P., Armesto. J, Di-Capua. D., Gonzalez-Drido. R., Lorenzo. H, Perez-Gracia. V., 2007, Digital Photogrammetry, GPR and Computational Analysis of Structural Damages in a Mediaeval Bridge, Engineering Failure Analysis, Vol. 14, Issue 8, pp. 1444-1457
- ASTM D5607-08, Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force
- BGS, British Geological Society, n.d., http://www.bgs.ac.uk/reference/gshp/gshp_report.html [accessed May 2018]
- Binda, L., Lenzi, G., Saisi, A., 1998, NDE of Masonry Structures: Use of Radar Tests for the Characterisation of Stone Masonries, NDT&E International, Vol. 31, Issue 6, pp.411-419.
- Bishop. I, Koor. N.P, 2000, Integrated Geophysical and Geotechnical Investigations of Old Masonry Retaining Walls in Hong Kong, Quarterly Journal of Engineering Geology and Hydrology, Vol. 33, Issue 4, pp. 335-349
- British Standards, BS1337-7:1990, Methods of test for soils for civil engineering purposes. Shear strength tests (total stress)
- Burgoyne, J., 1853, Revetments or Retaining walls, Corps of Royal Engineers, Vol. 3, pp. 154-159.
- CAPEB, ABPS, M. de Provence, CBPS, C. 84, and ENTPE, 2008, Pierre Seche -guide de bonnes pratiques de construction de murs de soutènement. ENTPE.

-
- CIBSE, 2015, Building Performance Modelling—CIBSE AM11–2015, CIBSE.
- Clarke, M., McCann, D., Forde, M., 2003, Application of Infrared Thermography to the Non-Destructive testing of Concrete and Masonry Bridges, *NDT&E International*, Vol. 36, pp. 265-275.
- Claxton, M., Hart, R.A., McCombie, P.F., Walker P.J., 2005, Rigid Block Distinct-Element Modelling of Dry-Stone Retaining Walls in Plane Strain, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, Issue 3, pp381-389.
- Colas, A. S., Morel, J. C., Garnier, D., 2012, Full Scale Field Trials to Assess Dry-Stone Retaining Wall Stability, *Engineering Structures*, Vol. 32, Issue 5, pp. 1215-1222.
- Colas, A. S., Morel, J. C., Garnier, D. 2008. Yield Design of Dry-Stone Masonry Retaining Structures-Comparisons with Analytical, Numerical and Experimental Data, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 32, Issue 14, pp 1817-1832.
- Cooper, M.R. 1986. Deflection and Failure Modes in Dry Stone Retaining Walls. *Ground Engineering*. Vol. 19. Issue 8, pp 29-33.
- Daniels, D., 2004, *Ground Penetrating Radar*, 2nd Edition, The Institution of Engineering and Technology.
- Dickens, J., Walker, P., 1996, Use of Distinct Element Model to Simulate Behaviour of Drystone Walls, *Structural Engineering Review*, Vol. 8, pp. 187-199.
- Dry Stone Walling Association, Revised by Agate, E., Adcock, S., 1999, *Dry Stone Walling*, BTCV
- Dry Stone Walling Association. 2008, *Dry Stone Walling Techniques and Traditions*. G W Belton Limited
- Engineeringtoolbox, n.d, http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html [accessed July 2015]
- Festrail, 2017, http://www.festrail.co.uk/pdf/steaming_through_snowdonia.pdf [accessed March 2018]

-
- Flint, R. C., Jackson, P. D., McCann, D. M., 1999, Geophysical Imaging Inside Masonry Structures, NDT&E International, Vol. 32, Issue 8, pp. 469-479. 175
- FLIR, 2011, Thermal Imaging Guidebook for Building and Renewable Energy Applications, http://www.flirmedia.com/MMC/THG/Brochures/T820325/T820325_EN.pdf [accessed July 2015]
- García-Suárez, A. M., Butler, C. J., 2006, Soil Temperatures at Armagh Observatory, Northern Ireland from 1904 to 2002, International Journal of Climatology, Vol. 26, pp. 1075-1089.
- Harkness, R., Powrie, W., Zhang, X., Brady, K., O'Reilly, M., 2000. Numerical Modelling of Full-Scale Test of Drystone Masonry Retaining Walls, Geotechnique, Vol.50, No 2, pp. 165-179.
- Healy J. C., 2008, Using Acoustic Emissions to Detect Damage in Historical Stone Masonry, Structures Congress 2008.
- Hugenschmidt, J., Kalogeropoulos, A., The Inspection of Retaining Walls using GPR, Journal of Applied Geophysics, Vol. 67, Issue 4, pp. 335-344
- Kavanagh, J., Bowers, K.H, Brady, K.C, 1999. The use of Ground Penetrating Radar in the Investigation of Masonry Retaining Walls, TRL Report 428, Transport Research Laboratory.
- Deidda, G., Ranieri, G., 2005. Seismic Tomography Imaging of an Unstable Embankment, Engineering Geology, Vol. 82, Issue 1, pp. 32-42
- Lubowiecka, I., Armesto, J., Arias, P., Lorenzo, H., 2009, Historic Bridge Modelling Using Laser Scanning, Ground Penetrating Radar and Finite Element Methods in the Context of Structural Dynamics, Engineering Structures, Vol. 31, Issue 11, pp. 2667-2676.
- Maierhofer, C., Leipold, S., 2001, Radar Investigation of Masonry Structures, NDT&E International, Vol. 34, Issue 2, pp. 139-147.
- McCombie, P.F., Morel, J. C., Garnier, D., 2016, Drystone retaining walls: Design, Construction and Assessment, Taylor and Francis, Boca Raton, FL, USA.

McCombie, P. F., Mundell, C., Heath, A. and Walker, P., 2012, Drystone Retaining Walls: Ductile Engineering Structures with Tensile Strength, *Engineering Structures*, Vol. 45, pp. 238-243.

Moropoulou, A., Avdelidis, N.P., Kouli, M., Karakas, K., 2001, An Application of Thermography for Detection of Delaminations in Airport Pavements, *NDT&T International*, Vol. 34, pp. 329-335

Mundell, C., 2009, Large Scale Testing of Drystone Retaining Structures, PhD Thesis, University of Bath: Department of Architecture and Civil Engineering.

Mundell, C., McCombie, P., Bailey, C., Heath, A., Walker, P., 2009, Limit-Equilibrium Assessment of Drystone Retaining Structures, *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, Vol. 162, Issue 4, pp. 203-212.

Omega, n.d, <http://www.omega.co.uk/literature/transactions/volume1/emissivityb.html> [accessed July 2015]

O'Reilly P. and Perry, J. 2009. Drystone Retaining Walls and their Modifications- Condition Appraisal and Remedial Treatment. CIRIA. London.

Pennock, S. R. and Jenks, C. H. J., 2014, Road surface and pavement condition assessment by high frequency GPR diffraction, *Proceedings of the 15th International Conference on Ground Penetrating Radar, GPR 2014*. IEEE, pp. 881-886.

Powrie, W., Harkness, R., Zhang, X., Bush, D., 2002. Deformation and Failure Modes of Drystone Retaining Walls, *Geotechnique*, Vol. 52, No 6, pp. 435 – 446

Prudden, H. 2003, Somerset Building Stone – A Guide, *Proceedings of Somerset Archaeological and Natural History Society*, Vol.146, pp. 27-36.

Rasouli, V. and Harrison, J. P. 2010, Assessment of Rock Fracture Surface Roughness using Riemannian Statistics of Linear Profiles, *International Journal of Rock Mechanics and Mining Sciences*, Vol. 47(6), pp. 940-948.

Ramana. Y.V., and Gogte. B.S. 1987, Dependence of Coefficient of Sliding Friction in Rocks on Lithology and Mineral Characteristics, *Engineering Geology*, Vol. 26, pp. 271-279.

Shigeishi, M., Colombo, S., Broughton, K. J., Rutledge, H., Batchelor, A. J., Forde, M. C., 2001, Acoustic Emission to Assess and Monitor the Integrity of Bridges, *Construction and Building Materials*, Vol. 15, Issue 1., pp.35-49.

Solla, M., Lorenzo, H., Novo, A., Rial, F. I., 2010, Ground-Penetrating Radar Assessment of the Medieval Arch Bridge of San Anton, Galicia, Spain, *Archaeological Prospection*, Vol. 17, pp.223-232.

Solla, M., Lorenzo, H., Rial, F. I., Novo, A., 2012, Ground-Penetrating Radar for the Structural Evaluation of Masonry Bridges: Results and Interpretational Tools, *Construction and Building Materials*, Vol. 29, pp. 458-465.

Standards for Highways, BD21 (2001), *The Assessment of Highways and Bridge Structures*

Villemus, B., 2004, *Etude des murs de soutènement en maçonnerie de pierres seches*, These de doctorat de l'Institut National des Sciences Appliquees et de l'Ecole Nationale des Travaux Publics de l'Etat, 247pp., Lyon.

Villemus. B., Morel, J. C., Boutin, C., 2007, Experimental Assessment of Dry Stone Retaining Wall Stability on a Rigid Foundation, *Engineering Structures*, Vol. 29, Issue 9, pp. 2124-2132.

Walker, P.J., Dickens, J.G., 1995, Stability of Medieval Dry-Stone Walls in Zimbabwe, *Geotechnique*, Vol. 45, pp. 141-147.

Walker, P., McCombie, P., Claxton, M., 2006, Plane Strain Numerical Model for Drystone Retaining Walls, *Geotechnical Engineering*, Vol. 159, pp. 1-7.

Warren, L.A., 2011, *Dry Stone Walling: The influence of Weathering and Construction Style on Sliding Stability*, MEng Dissertation, University of Bath.

Washer, G., Fenwick, R., and Bolleni, N., 2010, Effects of Solar Loading on Infrared Imaging of Subsurface Features in Concrete, *Journal of Bridge Engineering*, Vol. 15, pp. 384–390.

Weather Box, n.d, <http://weather.whiteboxtechnologies.com/wd-all#> [Purchased May 2014]

WUFI- WIKI, n.d, <http://www.wufi-wiki.com/mediawiki/index.php5/Hauptseite> [accessed March 2015]

Zhang. L., 2005, Engineering Properties of Rock, Vol. 4, Elsevier Science Ltd.

Zhang, X., Koutsabeloulis, N., Hope, S., Pearce, A., 2004, A Finite Element Analysis for the Stability of Drystone Masonry Retaining Walls, Geotechnique, Vol. 54, pp 57-60.

Appendices

Appendix 1 – Walling Studies, Additional Images

Appendix 2 – Council Study, Example Reports

Appendix 3 – Initial Study on Friction, Additional Information

Appendix 4 – Geophysics, GPR Images

Appendix 5 – Thermal Imaging, Additional Images and WUFI Data

Appendix 1

Walling Studies

Please find additional images taken during the study not included in other chapters which provide an insight into the wide range of walling styles present.

Also included are some images from France of more decorative constructions that also provide a functional use as retaining walls, and some image taken in Cornwall following a number of large storm events in early 2014.

A1.1 Additional Cornish walls

A1.2 Additional Images from the Ffestiniog Railway

A1.3 Additional French walls

A1.4 Storm damage images from Cornwall

A1.1 Additional Cornish walls

A1.1.1 Boscastle Cornwall



Image showing a low level horizontal constructed retaining wall using local slate. This is a non-typical construction method using this material. However the low level of this wall and hence relatively small forces acting on the rear of wall enable this construction here.



Typical Cornish bank construction showing an end detail including a gate post



Image showing the scale and extent of the use of drystone retaining walls at Boscastle which extend for the full length of the estuary and harbour wall constructions. It is also possible to see the tidal range these walls are subjected to by the water marks present.



Image showing two differing styles abutting one another, in this case possibly denoting a boundary between adjacent properties.



Image showing a vertically constructed retaining wall adjacent to the estuary which has significant vegetation growth. Many walls in this area show significant vegetation growth through their front face.

A1.1.2 Port Isaac



Image showing newly constructed walls forming a terrace to private gardens above.

A1.1.3 Marazian



Images showing a coursed wall retaining the sand dunes behind preventing encroachment onto the road.

A1.1.4 Mousehole – A series of images showing the change in construction style along the length of the harbour wall.





A1.1.5 Dartmoor



Random construction retaining wall on Dartmoor constructed from material found on the slope above.

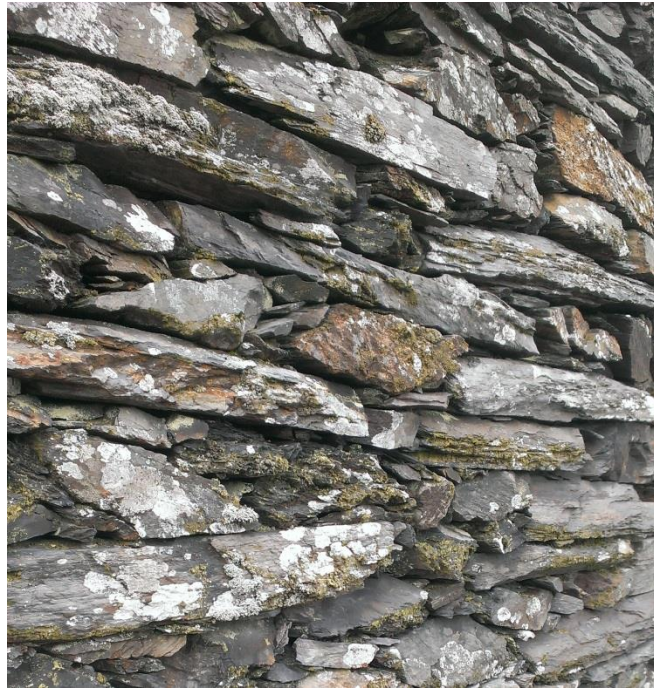
A1.2 Additional Images from the Ffestiniog Railway



Image showing one of the many culvers that go under the embankments (note the person stood next to the embankment for an idea of scale)



Image showing where the embankment meets a bridge over a small road. This section of wall had a more distinct construction styles than seen elsewhere, below.



Close up of wall construction above with bands of longer narrow stones with bands of smaller more angular stones between.



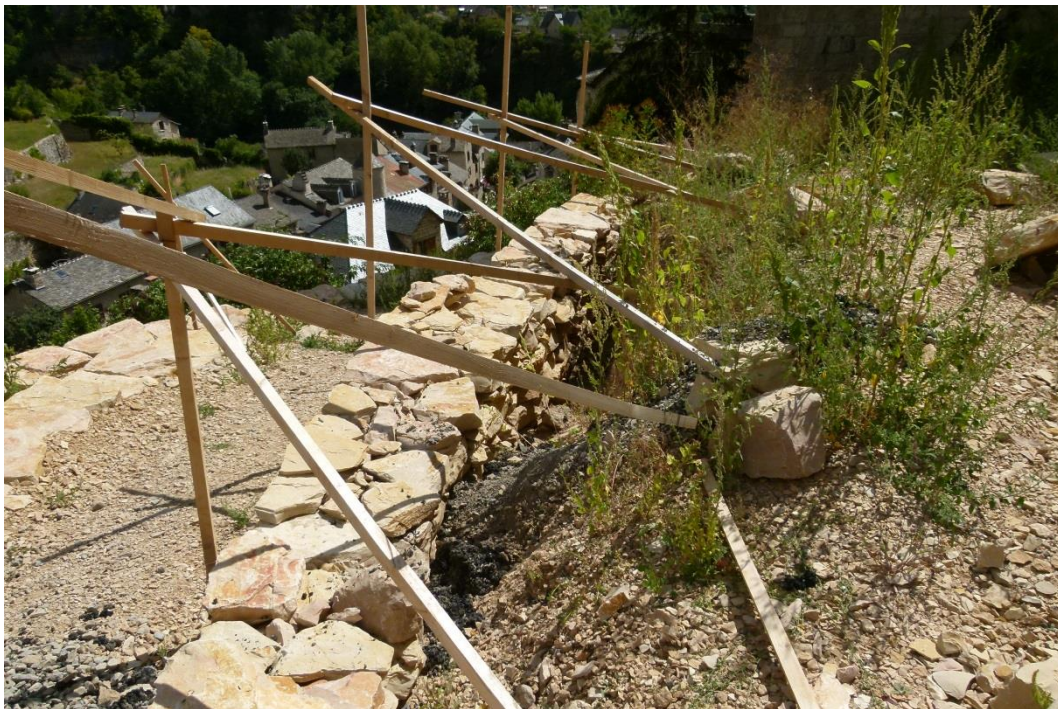
Retaining wall adjacent station platform with residential properties behind. This wall shows signs of having bulged but appears to be in good condition and relatively stable.

A1.3 Additional French walls

A1.2.1 St Enimie



Image showing one of the many terraced slopes in this area all predominantly constructed using drystone



One of the monastery walls under construction

A1.2.2 D998



Image showing the tight bend prior to the historic wall shown in figure 3.24 hence inducing forces not typically seen on drystone construction.

A1.2.3 L'Espinass – D35



Wall under construction showing decorative band. Image showing construction through wall below.



Construction through wall showing typical French construction of larger lapped stones throughout the wall thickness.



A newly constructed bridge, which though mortared using lime is constructed using dry-stone principles.

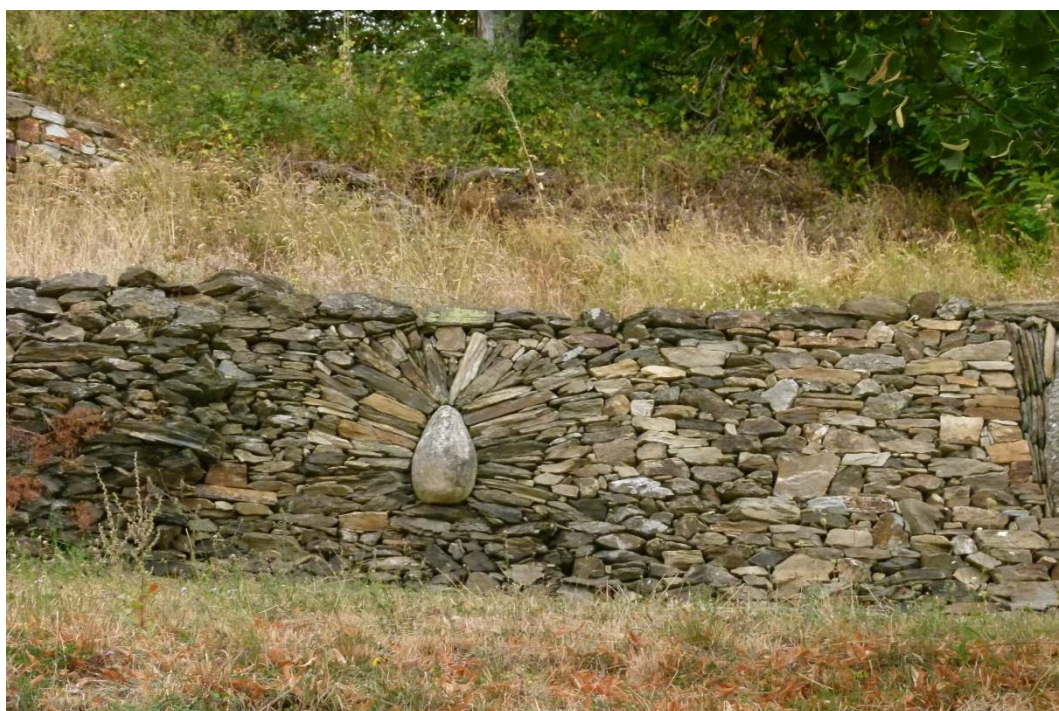


The original bridge the newly constructed bridge replaces.

A1.2.3 L'Espinass – Some of the artistic walls created by the artisans (for interest only)







A1.4 Storm damage images from Cornwall

A1.4.1 Port Gavern Additional Images



Damage to road above collapse



Ends of collapse showing wall construction and thickness, as well as signs of services effected



Material removed as a result of storm on beach

Appendix 2

Council Study

Please find examples of reports from Gloucester and Cornwall County Council showing the typical report layouts and information gathered.

In the interests of confidentiality all wall and council specific information has been removed to leave an outline report, showing typical report style only.

A2.1 Gloucester County Council Example Report



Gloucestershire Highways

WALL NAME

Wall No. **XXX**

Special Inspection Report

REPORT

EXAMPLE

Date – **REPORT DATE**



Gloucestershire Highways

WALL NAME

Wall No. **XXX**

Special Inspection Report

REPORT DATE

REPORT

EXAMPLE

JOB NUMBER			DOCUMENT REFERENCE		
		Originated	Checked	Authorised	Date
Revision	Purpose Description				



WALL NAME AND REF.

1. Introduction

- 1.1 As requested by **NAME** on the **DATE** an inspection of the highway retaining wall at Grid Reference **GRID REFERENCE** was carried out on the **DATE** **DATE** (See location plan).
- 1.2 The inspection was instructed following concerns about the condition of the wall expressed by **NAME AND DESCRIPTION E.G. HOME OWNER/ENGINEER** **REASON FOR REPORT** **REASON FOR REPORT**

2. Wall Details

- 2.1 The wall retains **DESCRIPTION OF RETAINED FEATURES E.G. ROAD NUMBER AND APPROX. LOCATION** **CONTINUED...** over a length of approximately **x** metres (Photo 1).
- 2.2 The wall is constructed of dry stone **GENERAL CONSTRUCTION E.G. RANDOM/COURSED** It supports a **DESCRIPTION OF SUPPORTED STRUCTURES E.G. VERGES/ROADS INC. DIMENSIONS AND ANY GRADIENTS** **DESCRIPTION OF AREA WALL FOUNDED INC. ANY GRADIENTS** (Photo 2).
- 2.3 The wall face comprises stone of typical size **xx** x **xx** mm.
- 2.4 **DESCRIPTION OF PARAPETS PRESENT/WHERE WALL TERMINATES IN RELATION TO GROUND LEVEL** **CONT...** (Photo 3).

3. Retaining Wall and Carriageway Condition

- 3.1 **GENERAL DESCRIPTION OF COLLAPSE/DEFORMATIONS** **CONTINUED... INC. DIMENSIONS** (Photo 4 and 7).
- 3.2 **OTHER STRUCTURAL ISSUES WITH WALL E.G. OPEN JOINTS/LOOSE OR MISSING STONES** **CONTINUED.....** (Photo 5).
- 3.3 **GENERAL STONE CONDITION AND WEATHERING** **CONT....** (Photo 6).
- 3.4 **VEGETATION PRESENT AND EFFECTS**
- 3.5 **ASSESSMENT OF CARRIAGEWAY** **CONT...** (Photo 7).
- 3.6 **DESCRIPTION OF GENERAL REPAIR** **CONT...** (Photo 8).



4. Repair Options

4.1 Option 1 - Structural Design Scheme

4.1.1

STRUCTURALLY DESIGNED OPTION DESIGN PARAMETERS

4.1.2

REQUIREMENT FOR GROUND INVESTIGATIONS

4.1.3

FEASIBILITY INC. WITH REGARD TO COSTS

4.1.4

COMPARISON TO EXISTING

5.2 Option 2 - Empirical Design Scheme ("Semi-Structural" Wall)

5.2.1

EMPERICAL OPTION BASED ON PREVIOUS PRACTISE/KNOWLEDGE

5.2.2

TRAFFIC CONTROL MEASURES REQUIRED FOR ANY WORKS

6. Conclusions

6.1

LIMITS OF ASSESSMENT REG. PARAMETERS KNOWN/REQUIRED/PERSONAL EXPERIENCE

6.2

GENERAL DRYSTONE COLLAPSE KNOWLEDGE

6.3

WALL FAILURE/CONDITION SUMMARY

6.4

OVERALL CONCLUSION AND RECOMMENDATION E.G. REPLACE/REPAIR/MONITOR

Enclosures: - 1. Photos (1 – 8 inclusive).
2. Location Plan



WALL NAME AND REF.

Photos

PHOTO: GENERAL VIEW 1 AT TOP OF WALL/ROAD LEVEL

Photo 1: - **GENERAL VIEW 1**

PHOTO: GENERAL VIEW 2 AT TOP OF WALL/ROAD LEVEL

Photo 2: - **GENERAL VIEW 2**



WALL NAME AND REF.

Photos

PHOTO: GENERAL VIEW 3 AT WALL LEVEL

Photo 3: - **GENERAL VIEW 3**

PHOTO: AREA OF COLLAPSE/DAMAGE

Photo 4: - **COLLAPSE/DAMAGE**



WALL NAME AND REF.

Photos

PHOTO: STRUCTURAL DEFECTS

Photo 5: - STRUCTURAL DEFECTS

PHOTO: AREA SHOWING GOOD CONDITION

Photo 6: - AREA OF GOOD CONDITION



PHOTO: CARRIAGEWAY CONDITION

Photo 7: - **CARRIAGEWAY CONDITION**

PHOTO: AREA OF COLLAPSE

Photo 8: - **COLLAPSE**



OS MAP EXTRACT: WALL LOCATION HIGHLIGHTED

Location Plan

A2.2 Cornwall County Council Example Report

Document Reference: **DOCUMENT REF.**

**CORNWALL COUNTY
COUNCIL**

SIGNATURE BLOCK

REPORT

EXAMPLE

**RETAINING WALL
ASSESSMENT
PROGRAMME**

ASSESSMENT REPORT

TITLE BLOCK

EXECUTIVE SUMMARY

SUMMARY OF ASSESMENT REQUIREMENTS

SUMMARY OF WALL STRUCTURE, RETAINED HEIGHT AND ASSESSED CAPABILITIES

Result of Assessment:

ASSESSED LOADING CAPABILITIES

Critical Load:

ASSESSED CRITICAL LOADING E.G. HIGHWAYS

Suggested Strengthening:

SUGGESTIONS AS REQUIRED

Monitoring Requirements:

SUGGESTIONS AS REQUIRED

Maintenance Issues:

ANY ISSUES

Loading Restrictions:

RESTRICITONS APPLIED

Known adjacent walls:

ANY KNOWN WALLS

ANY OTHER NOTES REGARDING CONDITION OR FACTORS THAT MAY AFFECT WALL

TABLE OF CONTENTS

	Page No.
EXECUTIVE SUMMARY	1
TABLE OF CONTENTS	2
DATA SHEET	3
1. INTRODUCTION	4
2. DESCRIPTION AND CONDITION OF THE STRUCTURE	4
3. ASSESSMENT	4
4. RESULT OF ASSESSMENT	5
5. RECOMMENDATIONS	5
APPENDIX 1 Approval In Principle	
APPENDIX 2 Calculations	
APPENDIX 3 Assessment Certificate	
APPENDIX 4 BE11 Form (Inspection Report)	

DATA SHEET

Structure Name	:	WALL REFERENCE		
Structure Ref. No.	:	SRTUCTIONE REFERENCE		
National Grid Ref.	:	GRID REFERENCE		
Length of Wall	:	xxx		
Retained Height	:	Maximum =	xxx	Average = xxx
Road Type	:	Road No.	xxx	ROUTE IMPORTANCE
Traffic Flow	:	AADT =	xxx	HGV = xxx YEAR
Location	:	DESCRIPTION OF LOCATION		
Land at base of wall	:	LAND USE		
Inspected by	:	NAME		
Date of inspection	:	DATE		
Owner of Structure	:	OWNER E.G. CORNWALL COUNTY COUNCIL		
Landowners details	:	DETAILS IF KNOWN		
District	:	DISTRICT		
Parish	:	PARISH		
Electoral Division	:	DIVISION		
Area Committee	:	COMMITTEE		
CCC Division	:	DIVISION		

1. INTRODUCTION

GENERAL INTRODUCTION

DETAILS OF ASSESSMENT - HA/HB LOADING CONSIDERED

2. DESCRIPTION AND CONDITION OF THE STRUCTURE

Detailed description and condition of the retaining wall is presented in the Inspection Report contained in Appendix B of the Approval in Principle (Appendix 1).

3. ASSESSMENT

HOW ASSESMENT CARRIED OUT E.G. VISUAL/CALCULATIONS

OVERVIEW OF WALL CONDITION AND ROAD ABOVE

OVERVIEW PARAPET CONDITION

CALCULATOIN METHODS USED FOR ASSESMENT E.G. HAND CALCULATIONS/SOFTWARE USED

4. RESULT OF ASSESSMENT

HB/HA CAPACITY OF WALL IN CURRENT CONDITION

STABILITY CALCULATION RESULTS FOR STATED ASSUMED WALL THICKNESSES

GENERAL CONDITION STATEMENT AND RISKS TO WALL

5. RECOMMENDATIONS

RECOMMENDATIONS FOR STRENGTHENING/REPLACEMENT

APPENDIX 1
Approval In Principle

EXAMPLE
REPORT

Document Reference: **DOCUMENT REF.**

SIGNATURE BLOCK

CORNWALL
COUNTY
COUNCIL

REPORT

EXAMPLE

RETAINING WALL
ASSESSMENT
PROGRAMME

APPROVAL IN
PRINCIPLE

TITLE BLOCK

**CORNWALL COUNTY COUNCIL
TRANSPORTATION AND ESTATES DEPARTMENT
THE DESIGN & MAINTENANCE CONSULTANCY**

APPROVAL IN PRINCIPLE (AIP)

1. NAME OF SCHEME: Retaining Wall Assessment Programme

1.1 Type of Highway:

ROAD NAME/NUMBER AND LOCATION

1.2 Permitted Traffic Speed:

xx kph

2. NAME OF STRUCTURE:

WALL REFERENCE

3. STRUCTURE TO BE ASSESSED

3.1 Description of Structure:

STRUCTURE TYPE I.E. RETAINING WALL AND RETAINED HEIGHT

3.2 Structural Type:

Dry Stone Wall

3.3 Foundation Type:

STATED IF KNOWN

3.4 Span Arrangements:

N/A.

3.5 Articulation Arrangements:

N/A.

3.6 Parapet Type:

BRIEF DESCRIPTION WITH DIMENSIONS

3.7 Proposed Arrangements for Inspection and Maintenance:

To be considered in Assessment.

4. ASSESSMENT CRITERIA

4.1 Live Loading:

4.1.1 HA Loading:

4.1.2 HB Loading:

BD CODES ASSESSMENT CARRIED OUT TO

4.1.3 Footway Live Loading: STATED IF APPLICABLE

4.1.4 Provision for exceptional abnormal loads: STATED IF APPLICABLE

4.1.5 Any special loading not covered above: STATED IF APPLICABLE

4.1.6 Departmental heavy or high load route requirements and arrangements being made to preserve the route:

STATED AS APPLICABLE

4.2 List of relevant documents from the Technical Approval Schedule (TAS) dated June 2001:

See Appendix E.

4.2.1 Additional relevant DOT standards published since the above edition of TAS:

ADDITIONAL STANDARDS

4.3 Proposed departures from Standards:

STATED AS APPLICABLE

4.4 Proposed method of dealing with aspects not covered by standards listed in 4.2 and 4.2.1:

PROPOSED METHODS OF DETERMINING WALL DEPTH IF APPLICABLE

5. STRUCTURAL ANALYSIS

5.1 Methods of analysis proposed for retaining walls:

PROPOSED NUMERICAL AND VISUAL ASSESSMENT METHODS

5.2 Description and diagram of idealised structure to be used for analysis:

FOUNDATION ASSUMPTIONS

5.3 Assumptions intended for calculations of structural element stiffness:

N/A

5.4 Proposed earth pressure coefficients (k_a , k_o or k_p) to be used in the assessment of earth retaining elements:

Angle of internal friction

=

 K_a

=

 K_p

=

PROPOSED SOIL PARAMETERS

6. GROUND CONDITIONS

GENERAL DESCRIPTION OF GROUND

7. CHECKING**7.1 Proposed category of Structure: CATEGORY****8. DRAWINGS AND DOCUMENTS****8.1 List of drawings and documents accompanying this submission:**

Appendix A - Location Plan, 'Bridge Card' and Relevant Drawings

Appendix B - Inspection Report

Appendix C - Photographs

Appendix D - Deflectograph Information.-Not used

Appendix E - Technical Approval Schedule 'TAS' (June 2001)

9. NOT USED**10. THE ABOVE IS AGREED SUBJECT TO THE AMENDMENTS AND CONDITIONS SHOWN BELOW:**

SIGNATURE AND DATE

APPENDIX A

Location Plan, 'Bridge Card' and Relevant Drawings

WALL REFERENCE

Name of Road: ROAD NAME

Road No. or Classification: ROAD NUMBER

Division: Ownership if not CCC:

Construction Type: CONSTRUCTION

Foundations: FOUNDATIONS

Retained Height: XXX m.

Length: XX m.

Width: XXm IF KNOWN

Batter: RECORDED BATTER

Parapet Type: PARAPET DIMENSION

Verge Width: XXm IF KNOWN

Drainage: DRAINAGE PROVIDED

Ancient Monument: IF APPLICABLE

Loading Restrictions IF APPLICABLE

Services: KNOWN SERVICES

Retaining Wall No: WALL NUMBER

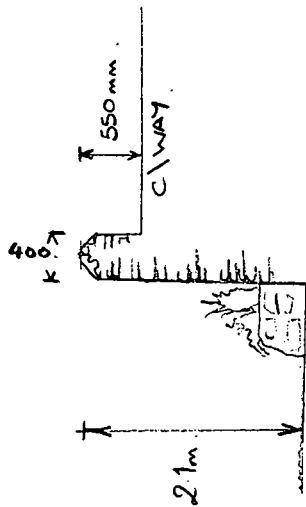
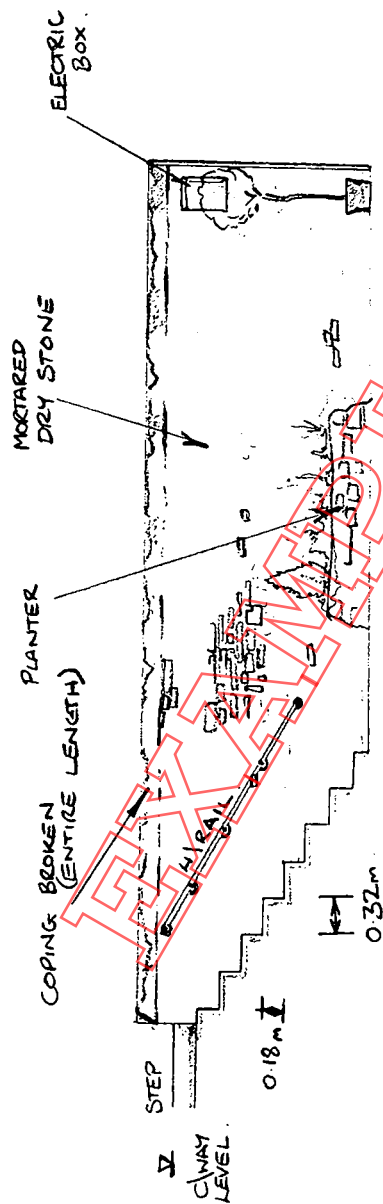
Scheme Ref: REFERENCE

Correspondence File No: FILE NUMBER

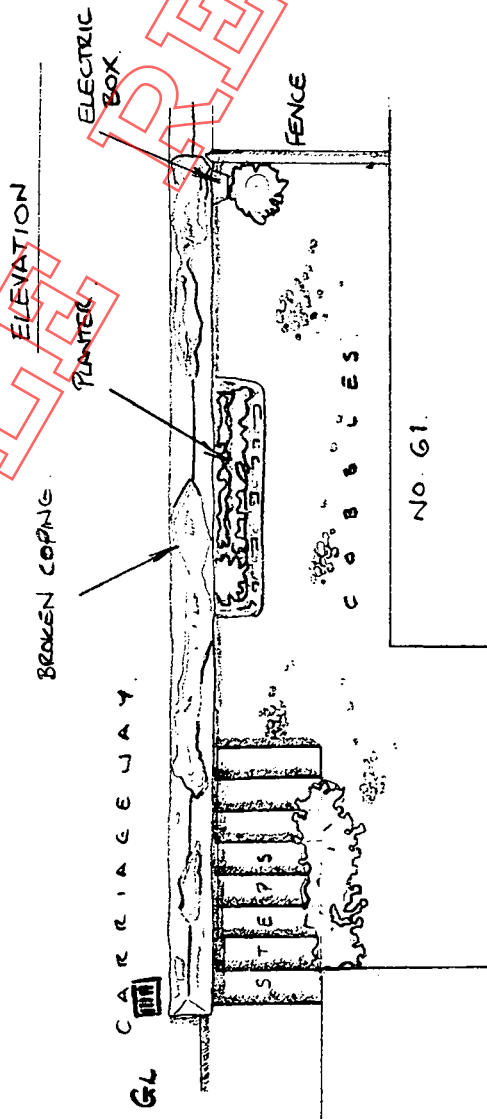
Design File No: FILE NUMBER



EXAMPLE



CROSS-SECTION CH 5

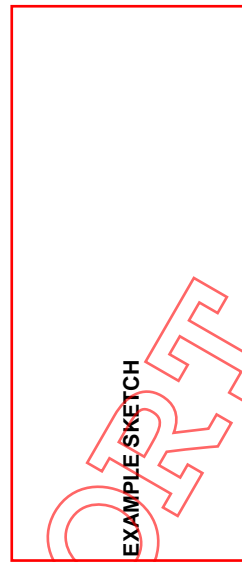


PLAN

- CH 8 END

- CH 5

- CH 0



REPORT

LOCATION PLAN: LARGE SCALE

EXAMPLE

EXAMPLE REPORT

LOCATION PLAN: SMALL SCALE

APPENDIX B
Inspection Report

EXAMPLE
REPORT

TABLE OF CONTENTS

	Page No.
DATA SHEET	2
1. INTRODUCTION	3
2. DESCRIPTION OF THE STRUCTURE	3
2.1 General Location	3
2.2 History	3
2.3 Specific Description	3
2.4 Traffic Loading	4
3. CONDITION OF THE STRUCTURE	4
3.1 Carriageway	4
3.2 Statutory Undertakers	4
3.3 Drainage	4
3.4 Fencing	4
3.5 Vegetation	4
3.6 Material	4
3.7 Deformation	4
3.8 Foundations	4
3.9 Summary	5

DATA SHEET

Structure Name	:	WALL REFERENCE
Structure Ref. No.	:	SRTUCTION REFERENCE
National Grid Ref.	:	GRID REFERENCE
Length of Wall	:	xxx
Retained Height	:	Maximum = xxx Average = xxx
Road Type	:	Road No. xxx ROUTE IMPORTANCE
Traffic Flow	:	AADT = xxx HGV = xxx YEAR
Location	:	DESCRIPTION OF LOCATION
Land at base of wall	:	LAND USE
Inspected by	:	NAME
Date of inspection	:	DATE
Owner of Structure	:	OWNER E.G. CORNWALL COUNTY COUNCIL
Landowners details	:	DETAILS IF KNOWN
District	:	DISTRICT
Parish	:	PARISH
Electoral Division	:	DIVISION
Area Committee	:	COMMITTEE
CCC Division	:	DIVISION

1. INTRODUCTION

INTRODUCTION: DATE OF INSPECTION/WHO CARRIED IT OUT/ FINDINGS REPORTED

2. DESCRIPTION OF THE STRUCTURE

2.1 General Location

LOCATION DESCRIPTION

2.2 History

PREVIOUS WALL HISTORY

2.3 Specific Description

The wall elevation, sections and site plan are shown on the 'Bridge card' included in Appendix A and the relevant photographs in Appendix C.

GENERAL WALL DESCRIPTION LENGTH/HEIGHT/OTHER FEATURES OF NOTE

SERVICES

PARAPET DESCRIPTION

OTHER EXTERNAL FACTORS THAT MAY AFFECT WALL

2.4 Traffic loading

AVERAGE TRAFFIC LOADING FOR WALL INC NORMAL TRAFFIC, HGVS AND ABNORMAL LOADING

3. CONDITION OF THE STRUCTURE

3.1 Carriageway

DEFLECTOMETRY INFORMATION AVAILABLE/GENERAL CARRIAGEWAY CONDITION

3.2 Statutory Undertakers

ANY LOCATION PLAN REQUESTS

3.3 Drainage

DRAINAGE PRESENT IN OR BEHIND WALL

3.4 Fencing

ANY FENCES PRESENT IN AREA

3.5 Vegetation

VEGETATION EFFECTING WALL

3.6 Material

CONSTRUCTION MATERIALS AND TYPICAL STONE SIZE. GENERAL CONDITION OF FACE

3.7 Deformation

ANY DEFORMATIONS OR MISSING STONES TO WALL AND PARAPET

3.8 Foundations

ANY ASSESSMENT CARRIED OUT

3.9 Summary

CONDITION SUMMARY. ANY CONCERNS AND REPAIRS REQUIRED

EXAMPLE REPORT

APPENDIX C

Photographs

EXAMPLE

REPORT

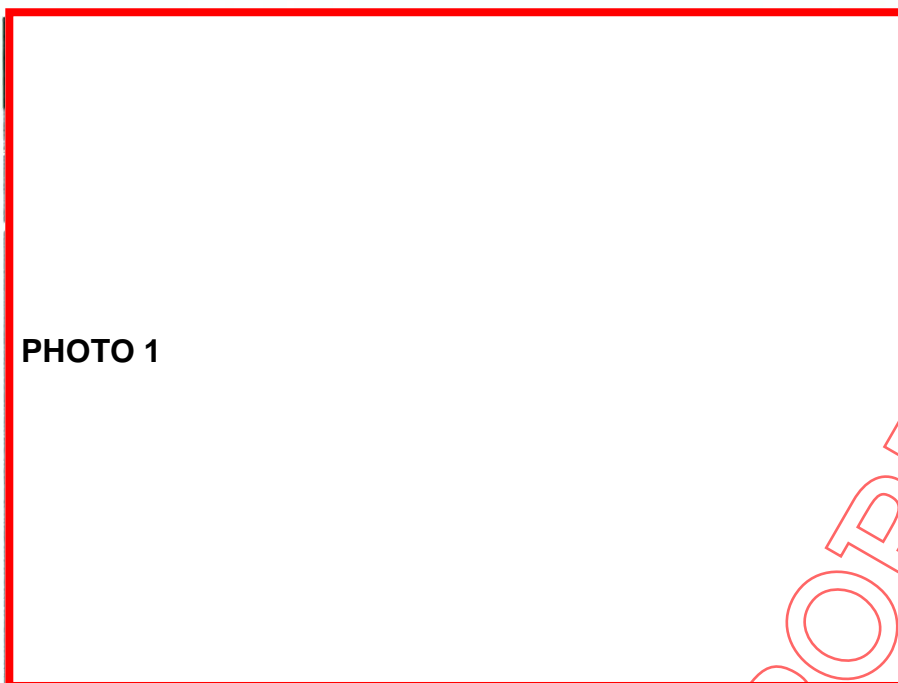


PHOTO 1

Photo 1

WALL REFERENCE

GENERAL VIEW WALL FEATURES

DATE

Photo 2

WALL REFERENCE

GENERAL VIEW WALL FEATURES

DATE

PHOTO 2

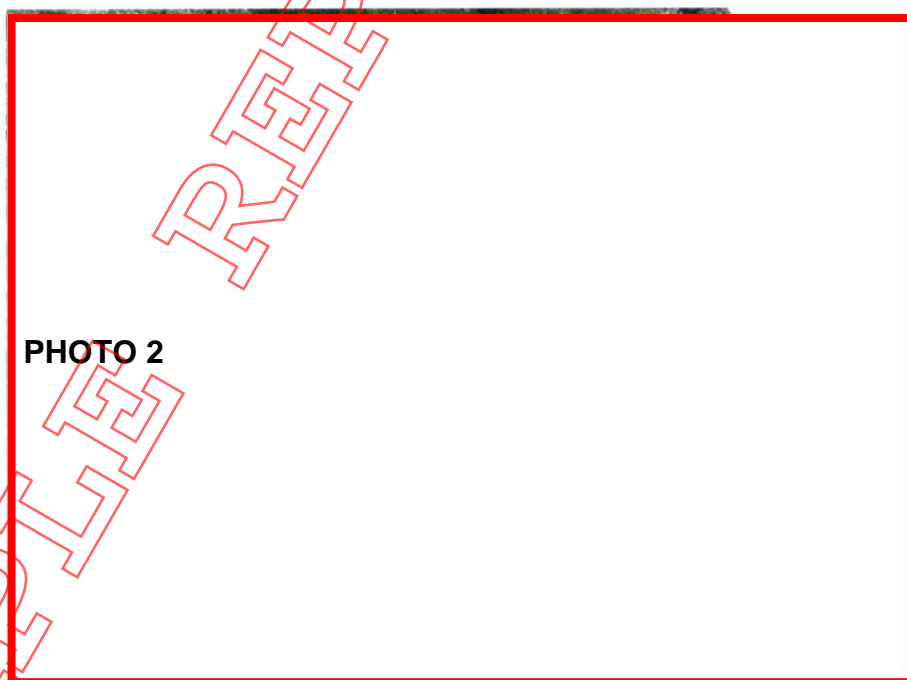


Photo 3

WALL REFERENCE

GENERAL VIEW WALL FEATURES

DATE

PHOTO 3



APPENDIX D

Deflectograph Information

No deflectograph information is available for this stretch of carriageway.

APPENDIX E

Technical Approval Schedule 'TAS' (June 2001)

REPORT

EXAMPLE

APPENDIX E

TECHNICAL APPROVAL SCHEDULE (TAS) June 2001

Rev: 0

SCHEDULE OF DESIGN AND ASSESSMENT DOCUMENTS RELATING TO BRIDGES AND STRUCTURES CARRYING HIGHWAYS (All documents are taken to include revisions current at date of the TAS).

1. BRITISH STANDARDS

STANDARDS USED

2. MISCELLANEOUS

STANDARDS USED

3. TECHNICAL MEMORANDUM

STANDARDS USED

4. DEPARTMENTAL STANDARDS

4.1 TRAFFIC ENGINEERING AND CONTROL

STANDARDS USED

4.2 BRIDGES AND STRUCTURES

STANDARDS USED

5. ADVICE NOTES

5.1 BRIDGES AND STRUCTURES

STANDARDS USED

STANDARDS USED

5.2 HIGHWAYS

STANDARDS USED

APPENDIX 2

Calculations

EXAMPLE
REPORT

REPORT

HAND CALULATIONS AND SOFTWARE PRINT OUTS

EXAMPLE

APPENDIX 3
Assessment Certificate

EXAMPLE
REPORT

**The Design Consultancy
Structures Group**

ASSESSMENT CERTIFICATE

CERTIFICATE F

1. **STRUCTURE CERTIFIED**

i. It has been assessed in accordance with:
The Approval in Principle Reference No. **REFERENCE**

ii. The assessed capacity of the structure is as follows:-
CAPACITY HA/HB LOADING

iii. The unique numbers of the drawings used for the assessment are :- **XX**

Signed: **SIGNED AND DATED**

Name:

Date:

Signed:

Name:

APPENDIX 4

BE11 Form (Inspection Report)

EXAMPLE REPORT

Appendix 3

Initial Study on Friction

A3.1 Stone Shearing Results

Full set of graphs from shear testing of:

A3.1.1 Quarry Limestone,

A3.1.2 A Weathered Limestone

A3.1.3 Morte Slate.

A3.2 Cotswold Wall Investigation

Stereographical projects for each wall considered along with other data recorded.

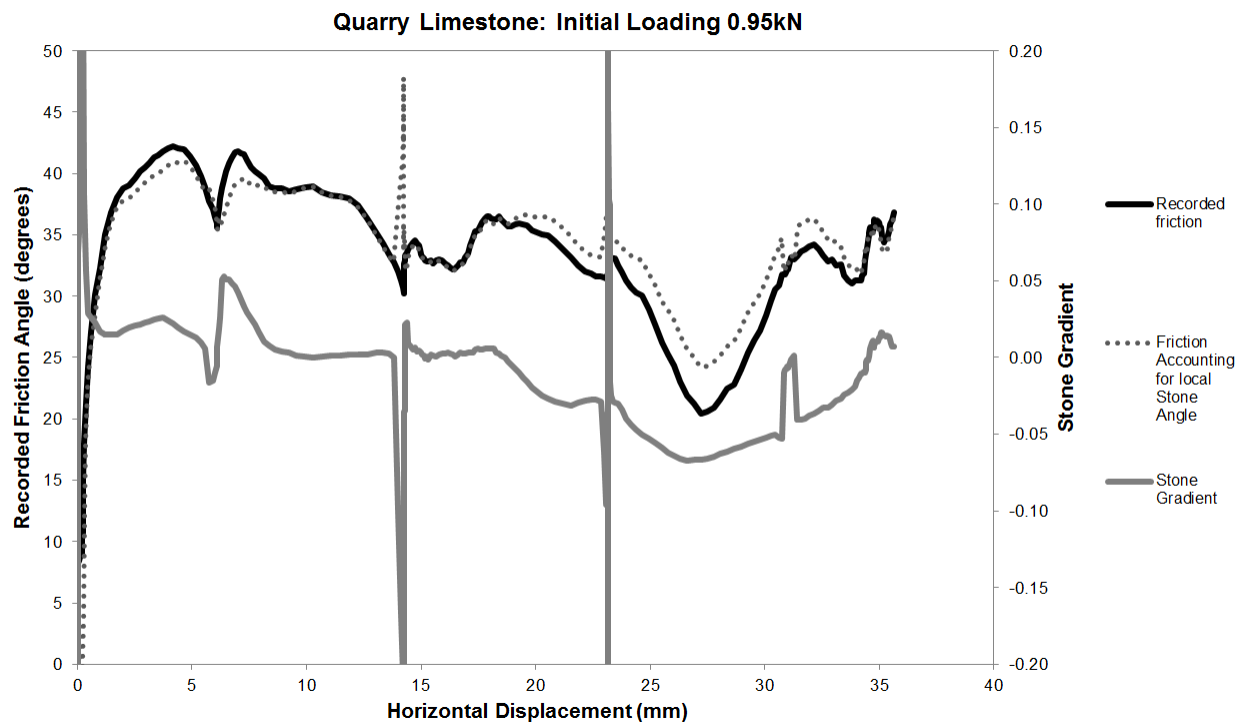
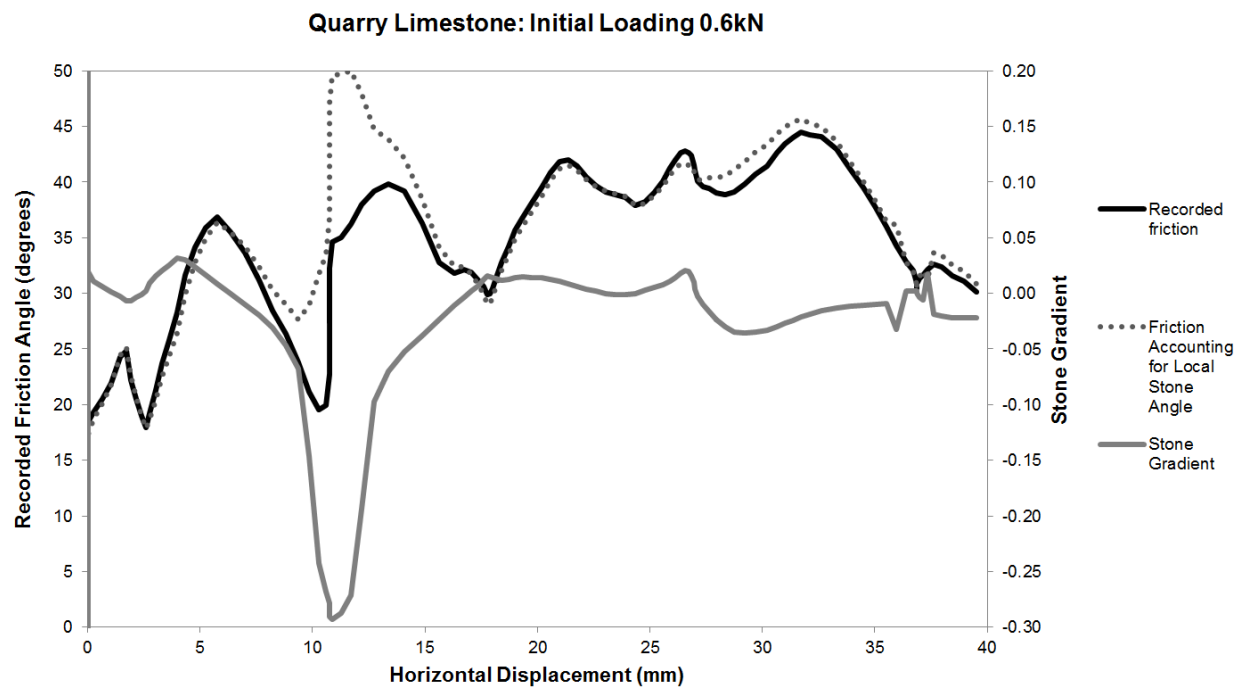
A3.1 Stone Shearing Results

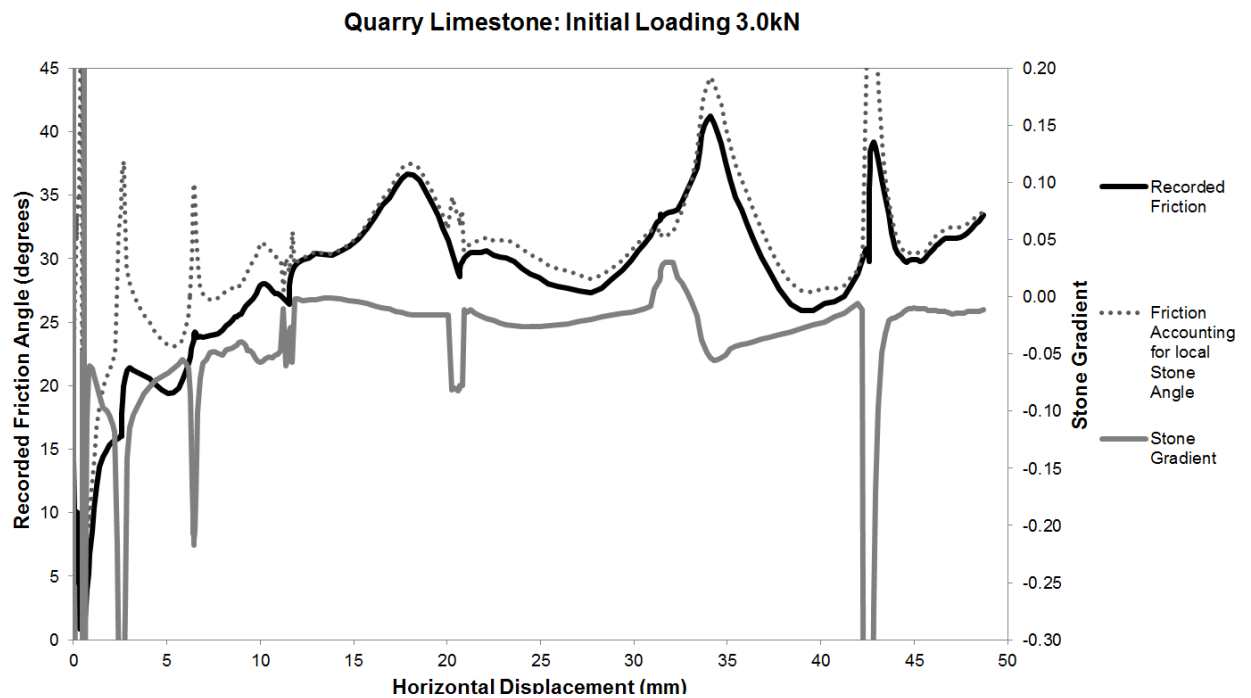
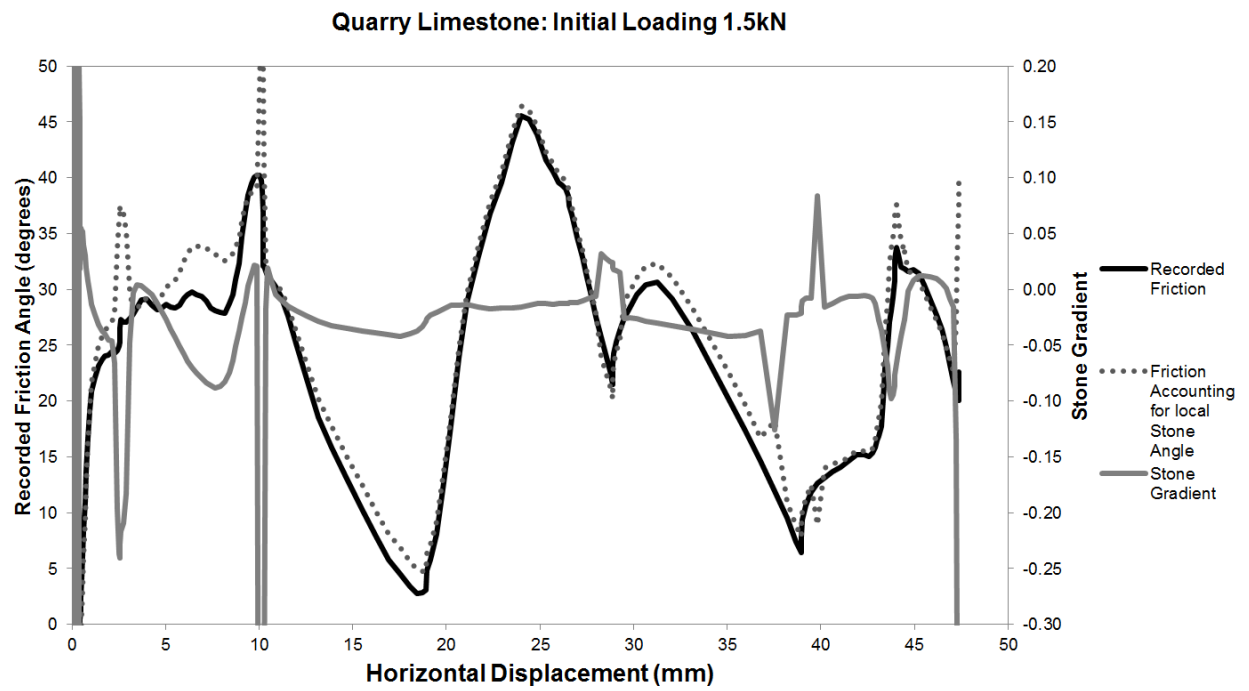
A3.1.1 Quarry Limestone

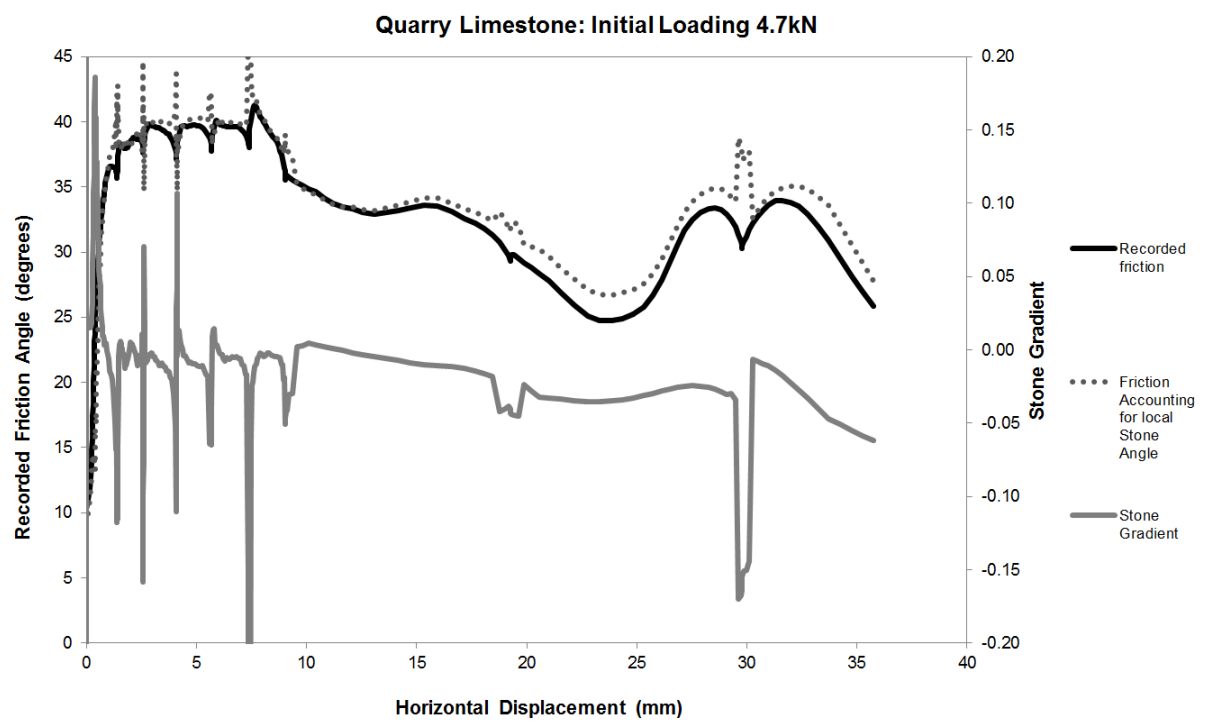
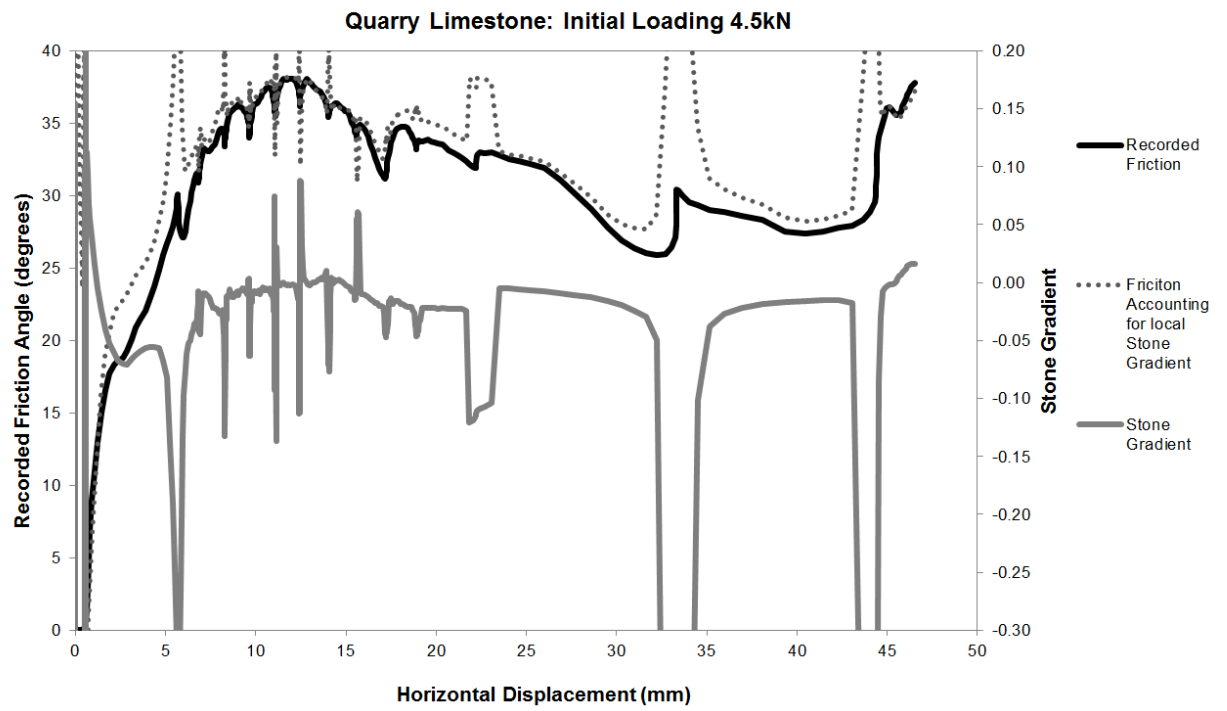
A3.1.2 Weathered Limestone

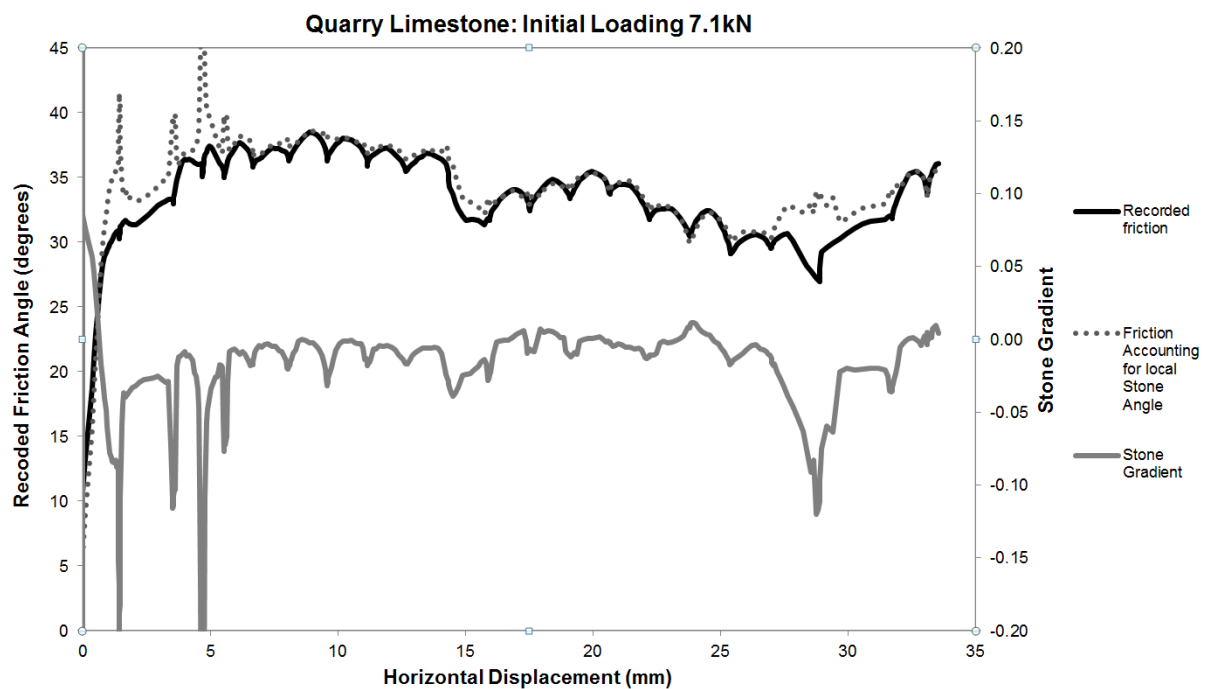
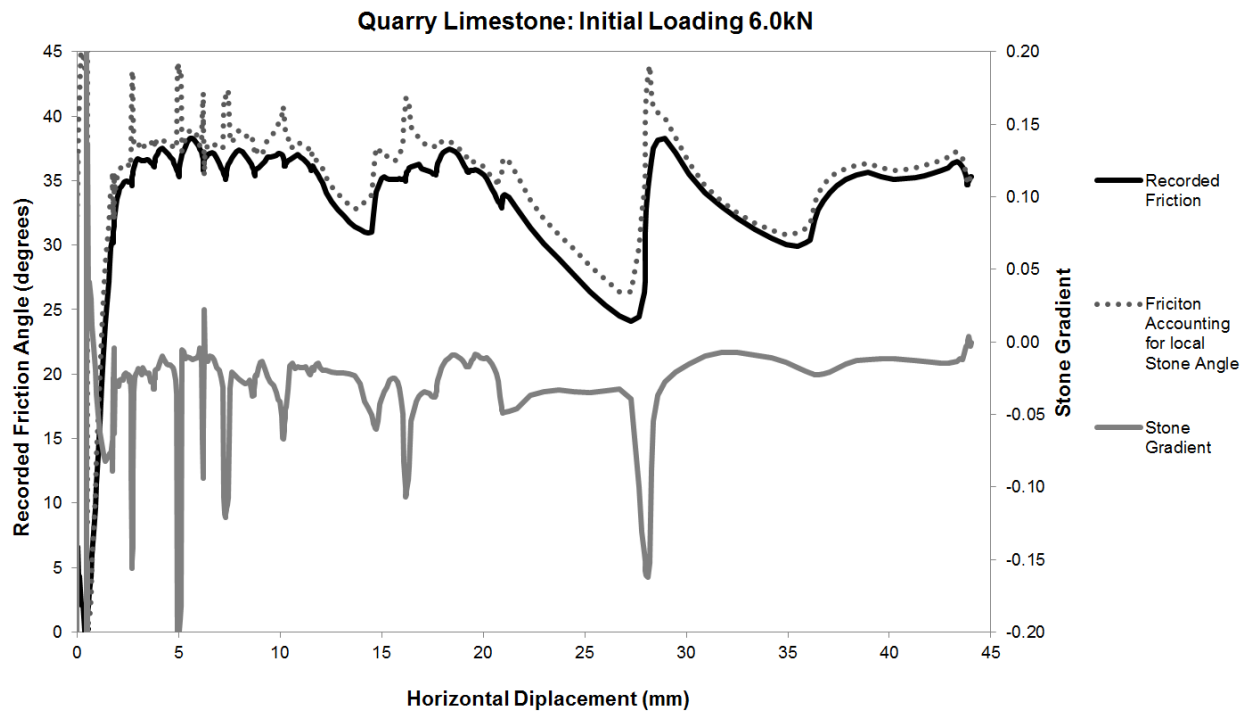
A3.1.3 Morte Slate

A3.1.1 Quarry Limestone

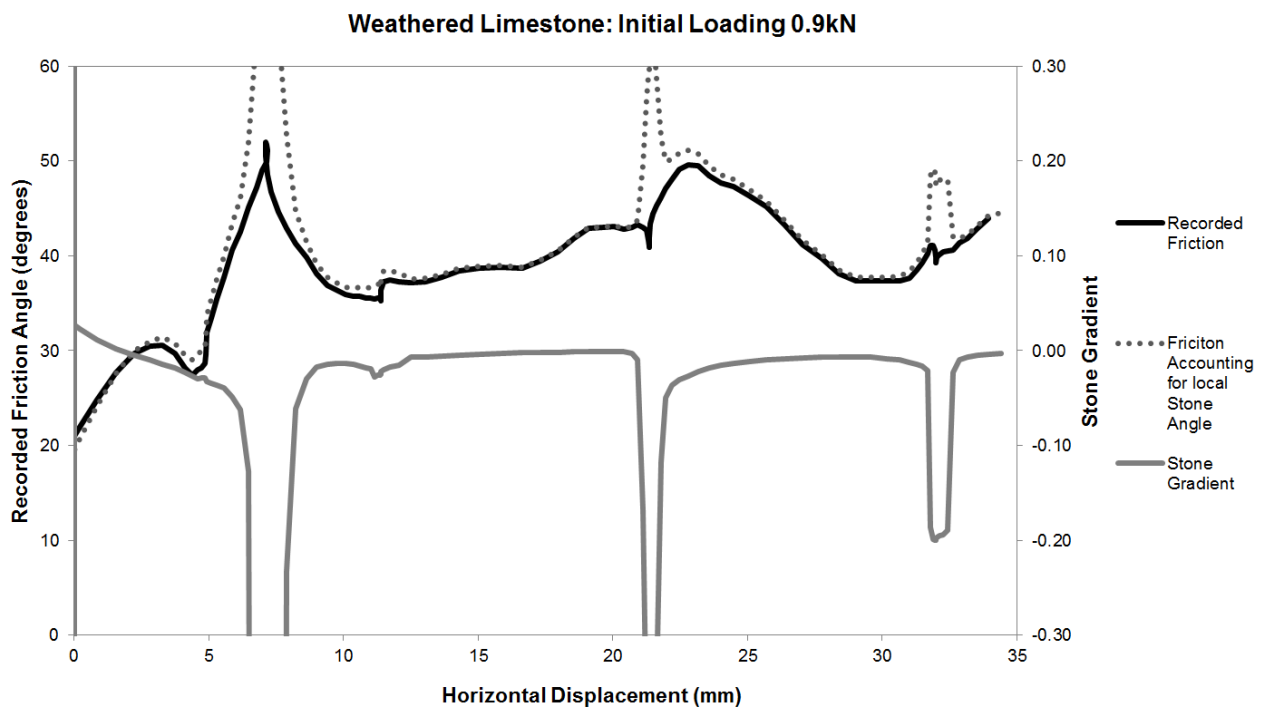
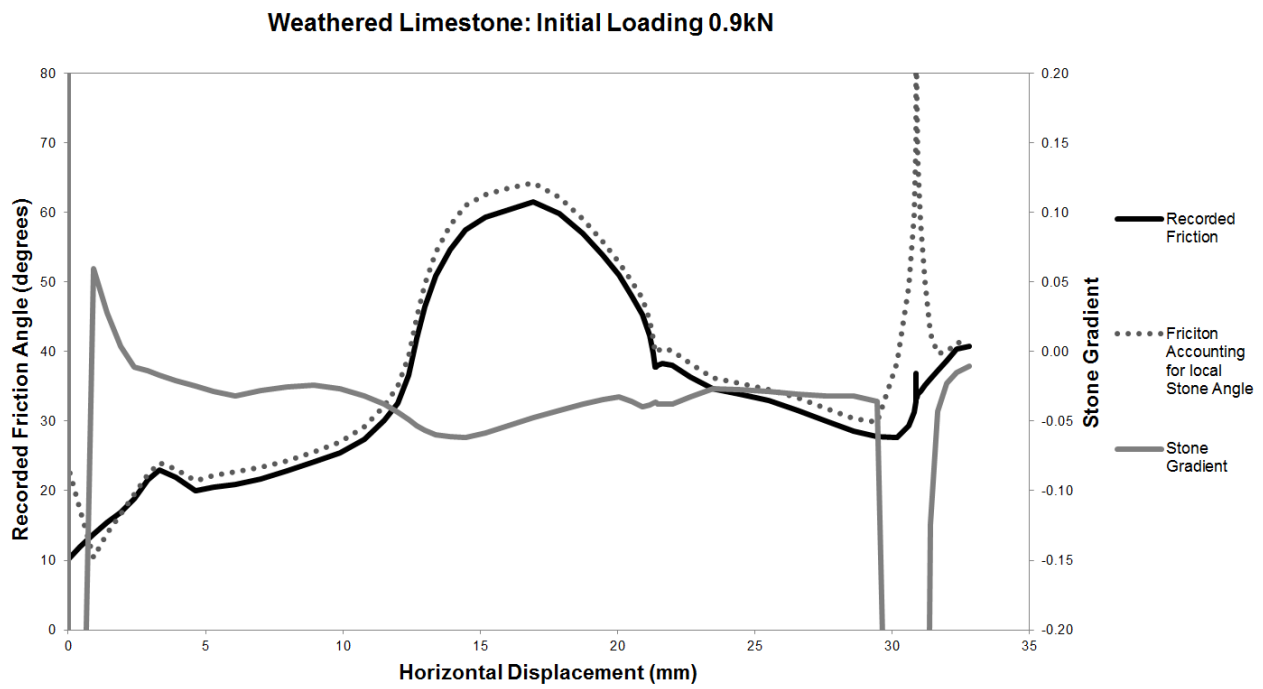


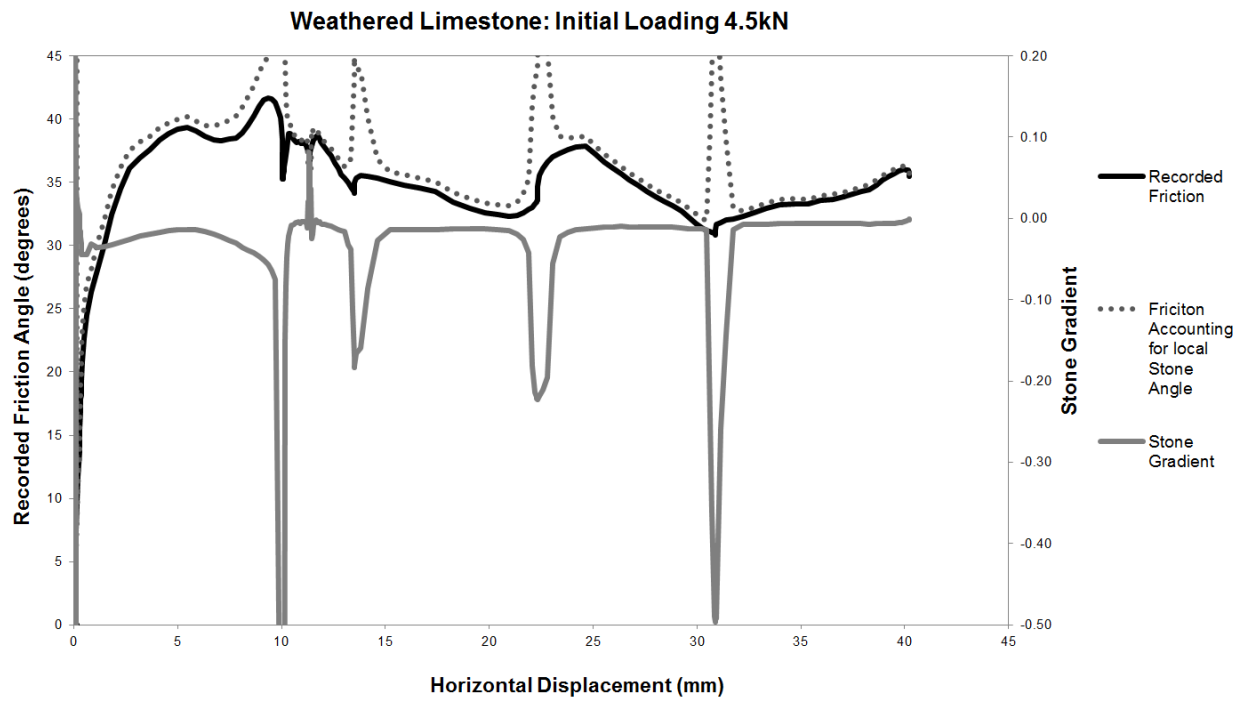
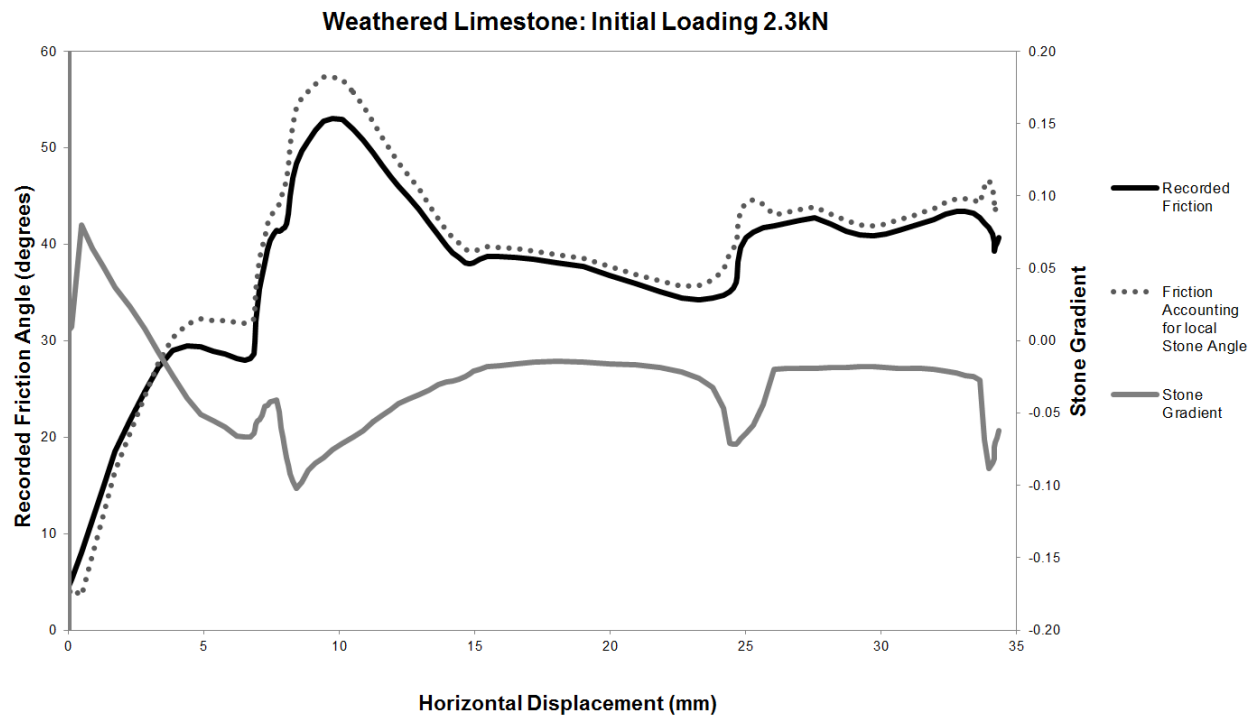


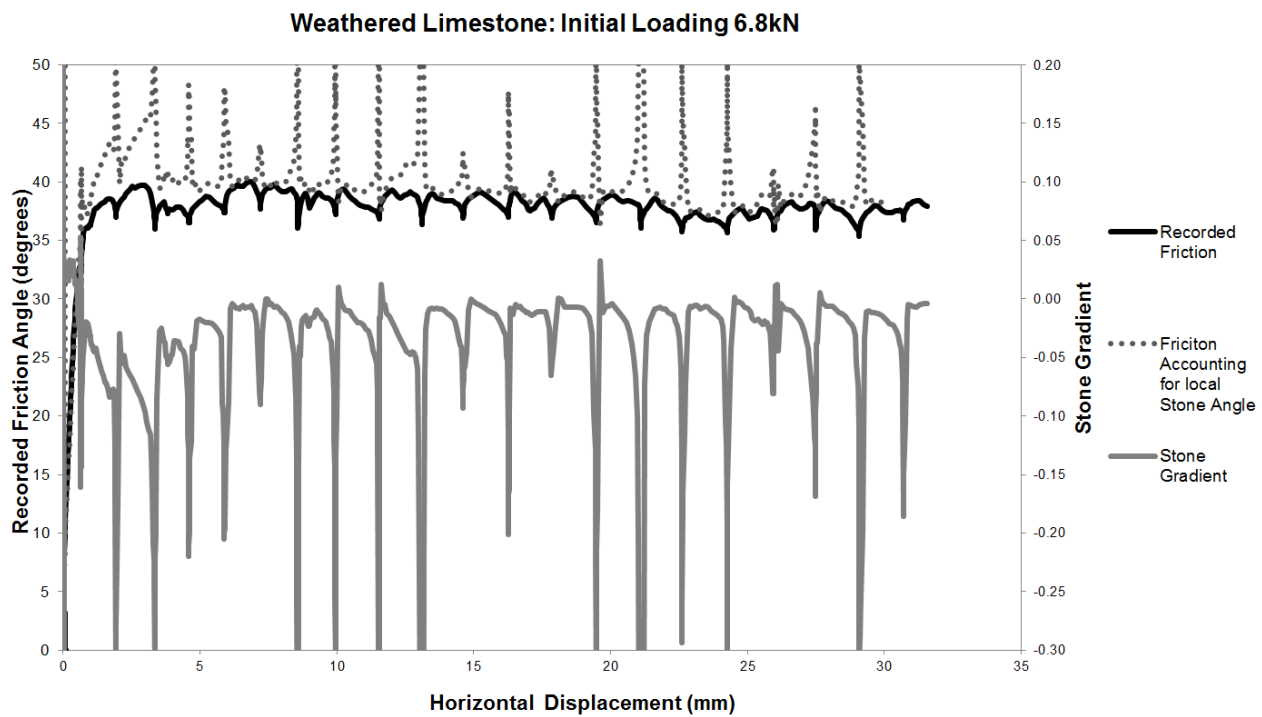
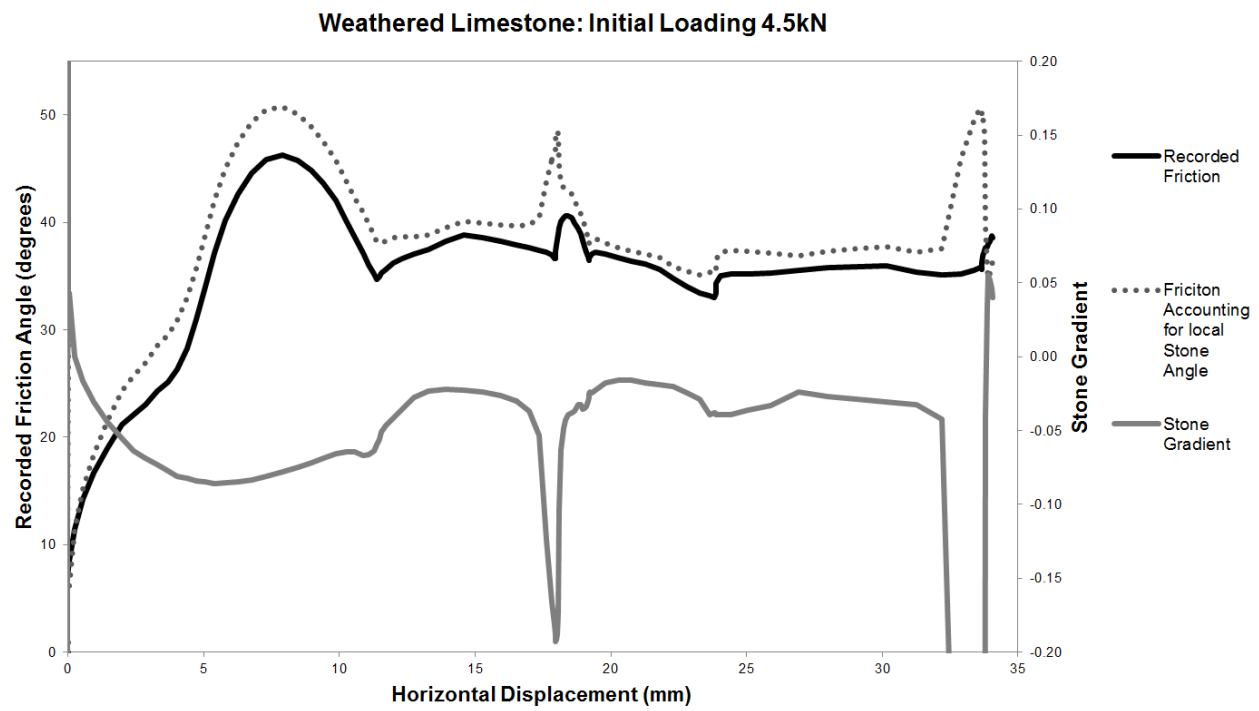


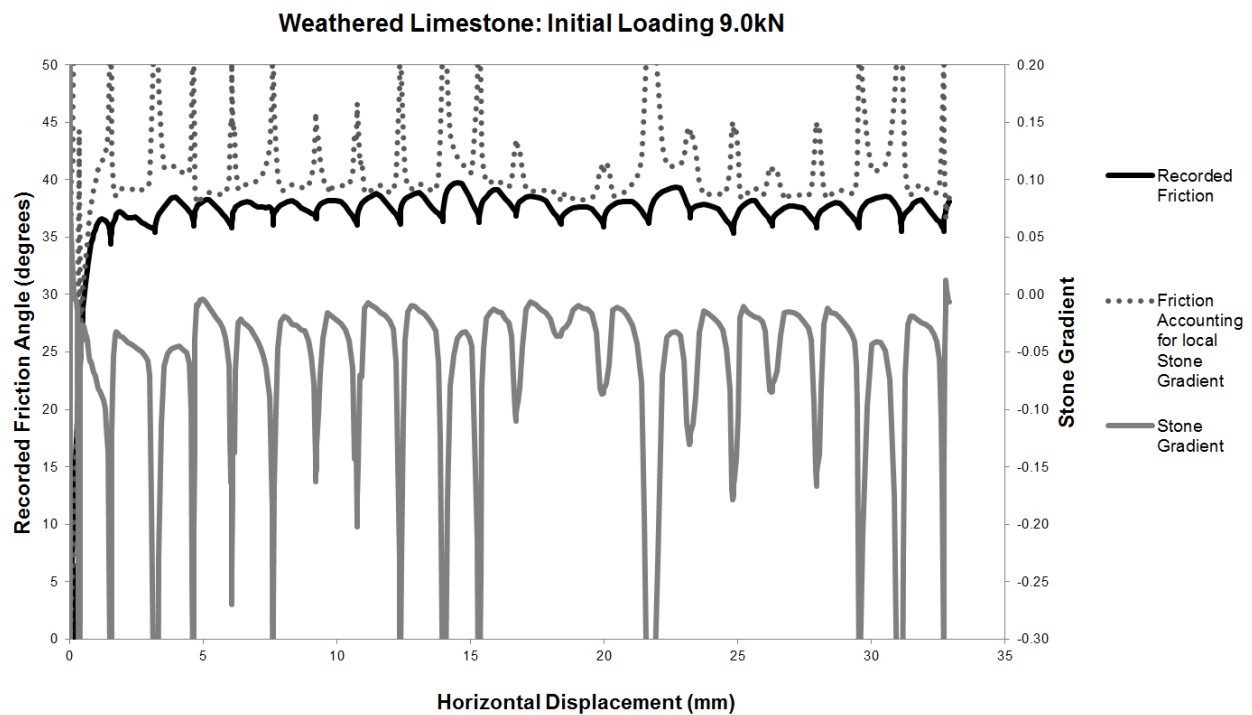
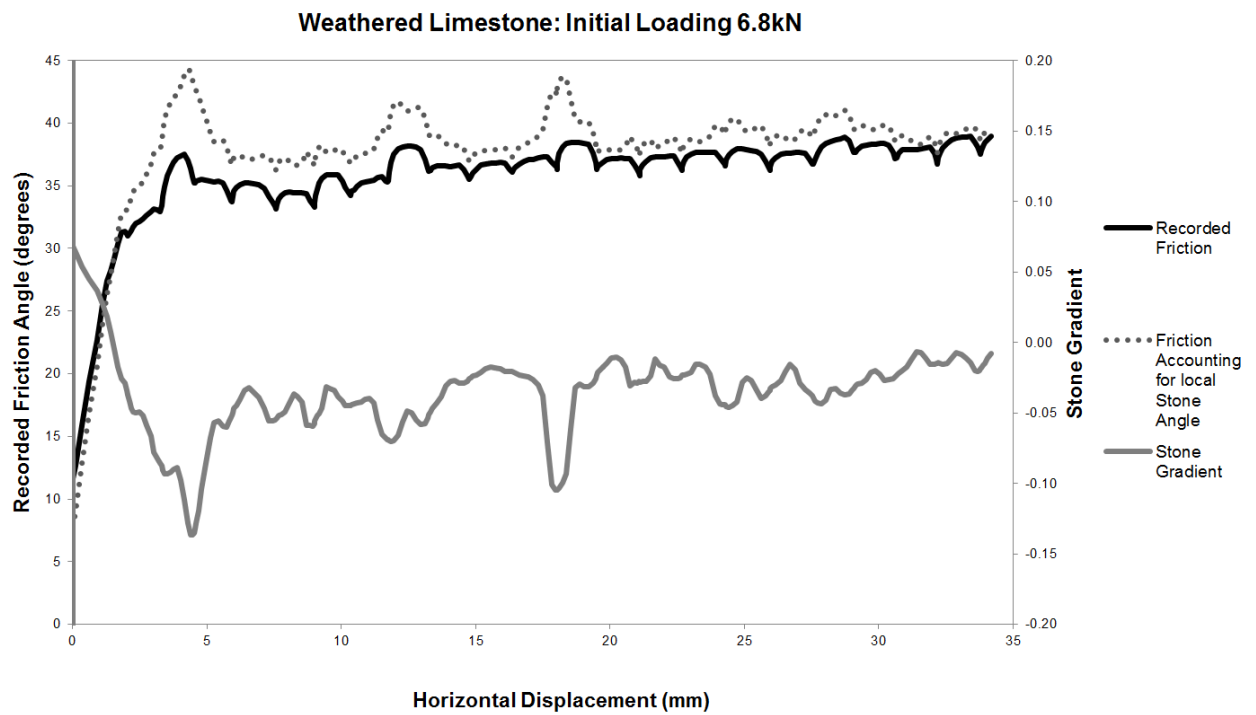


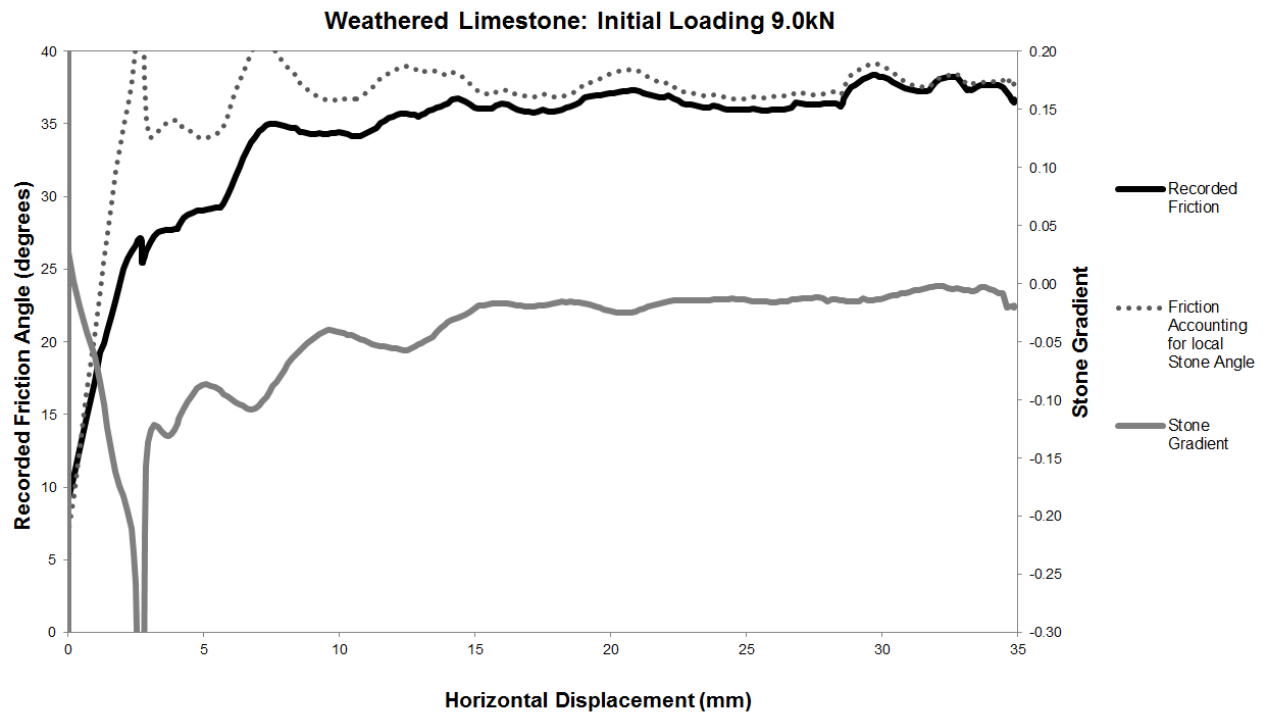
A3.1.2 Weathered Limestone



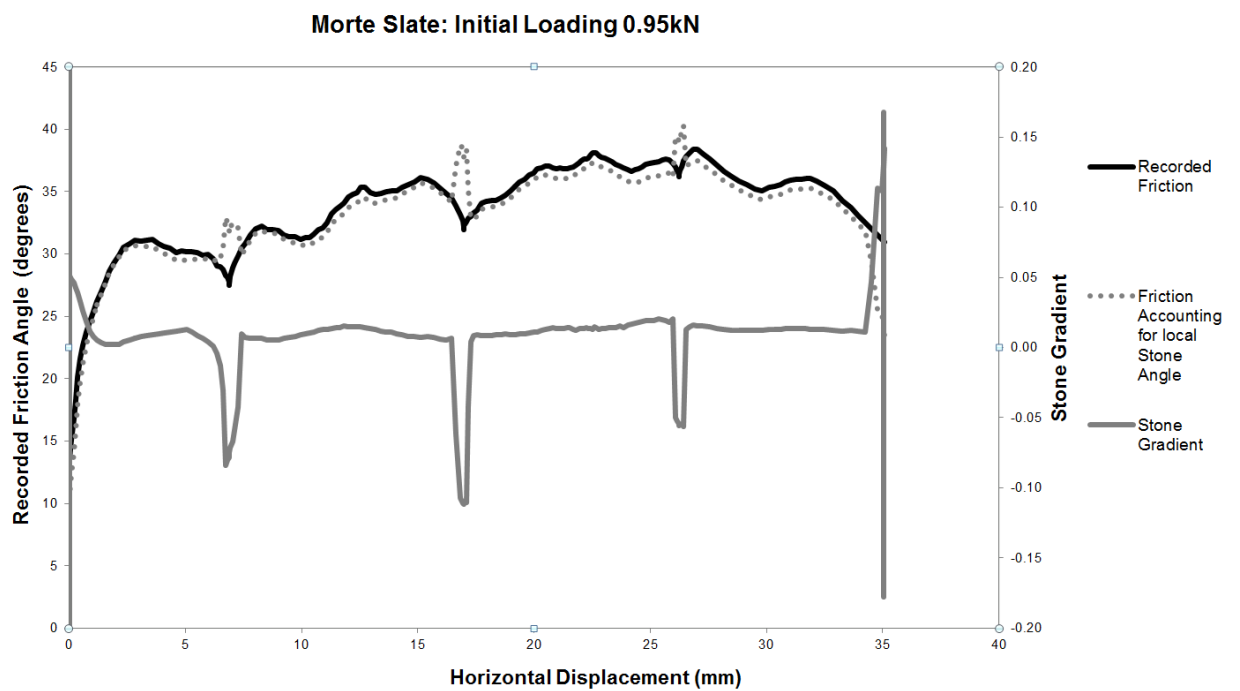
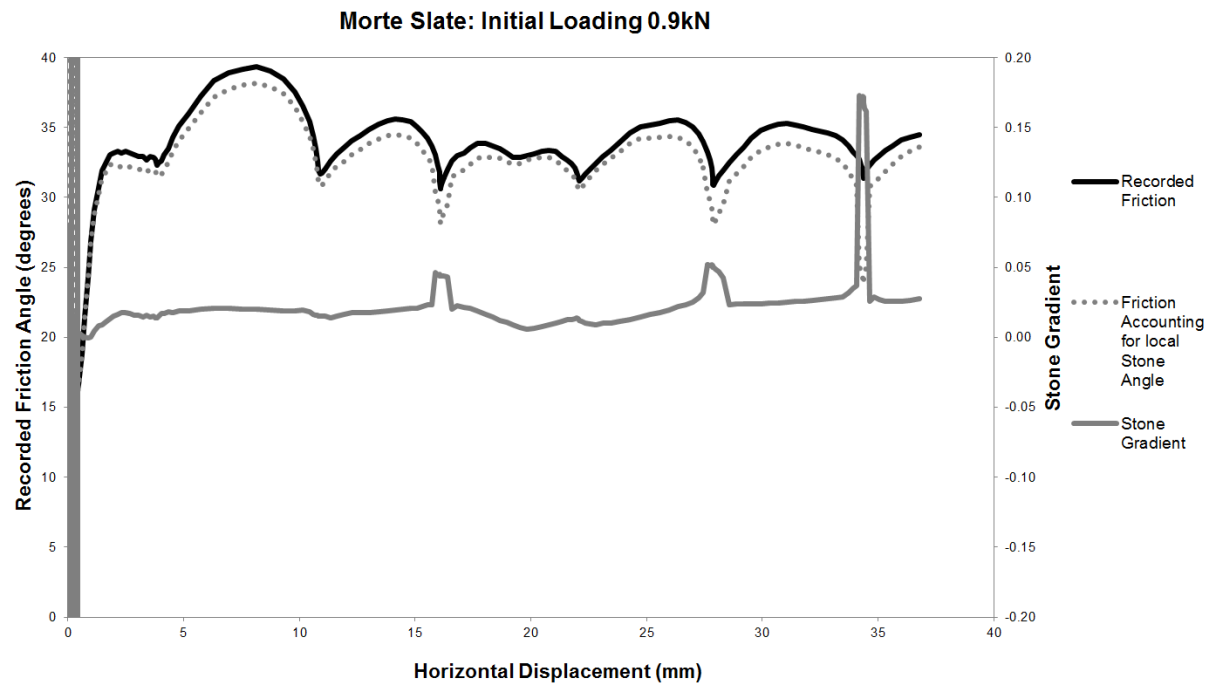


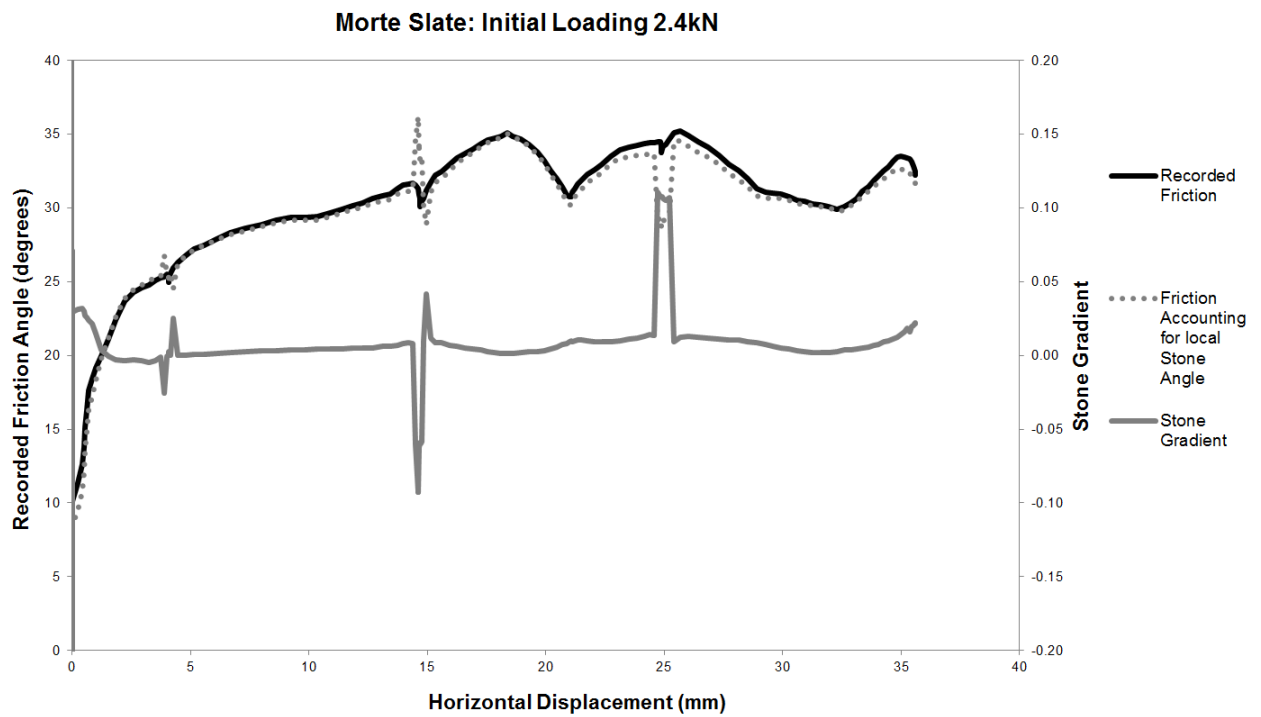
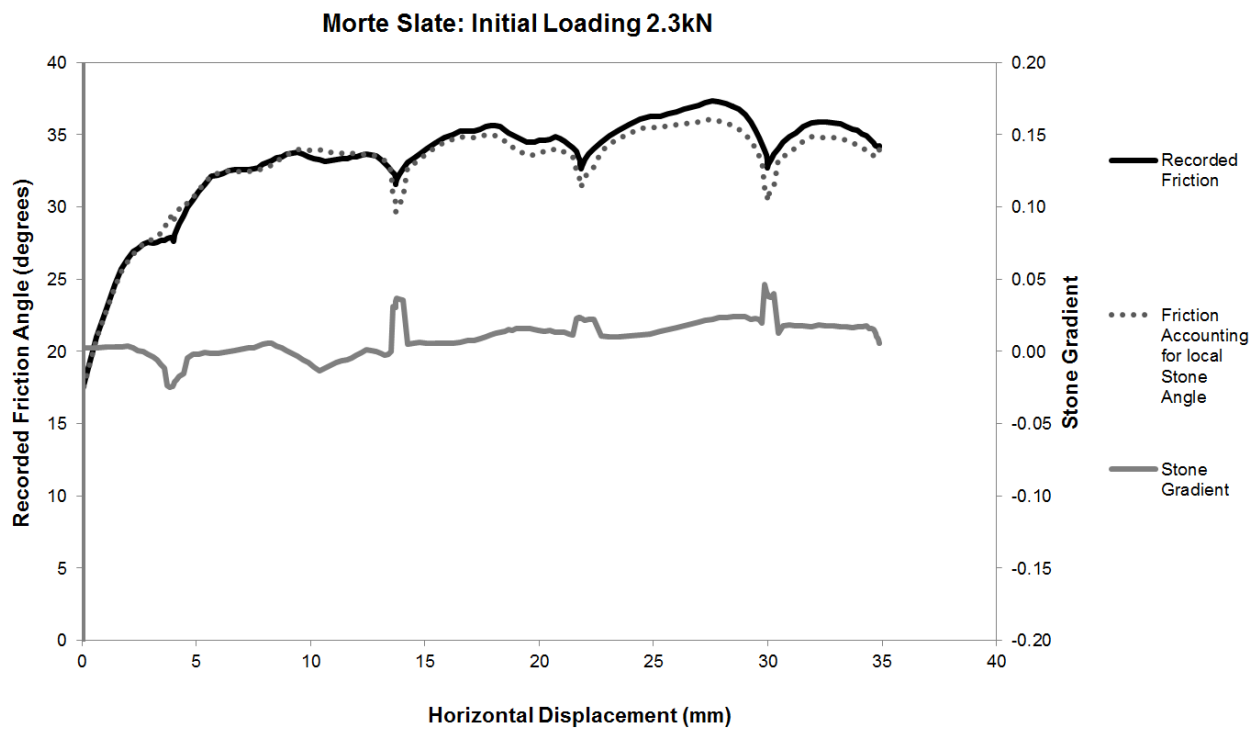


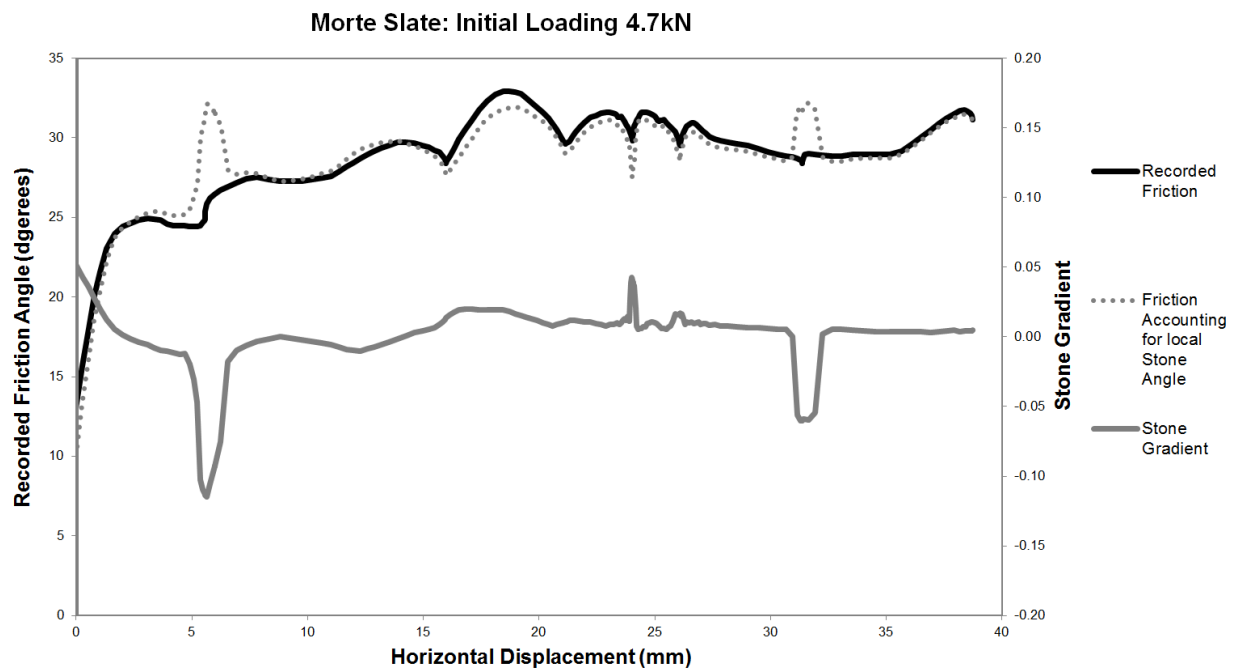
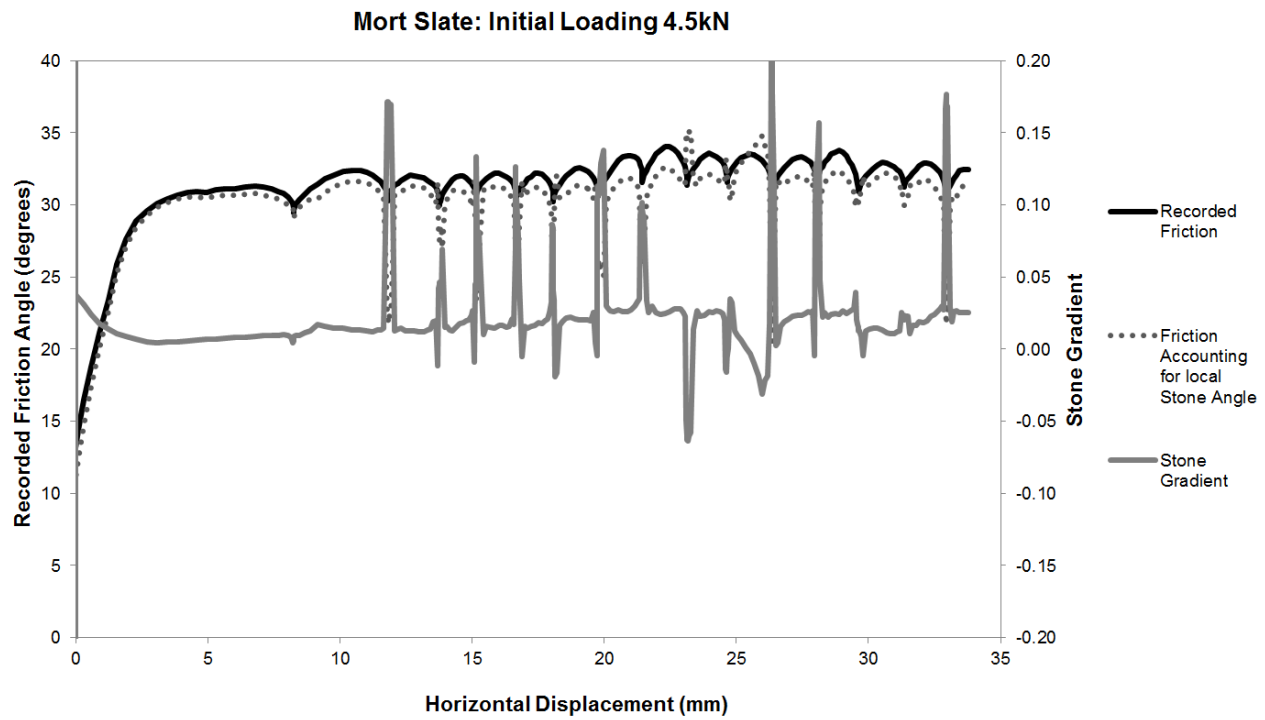


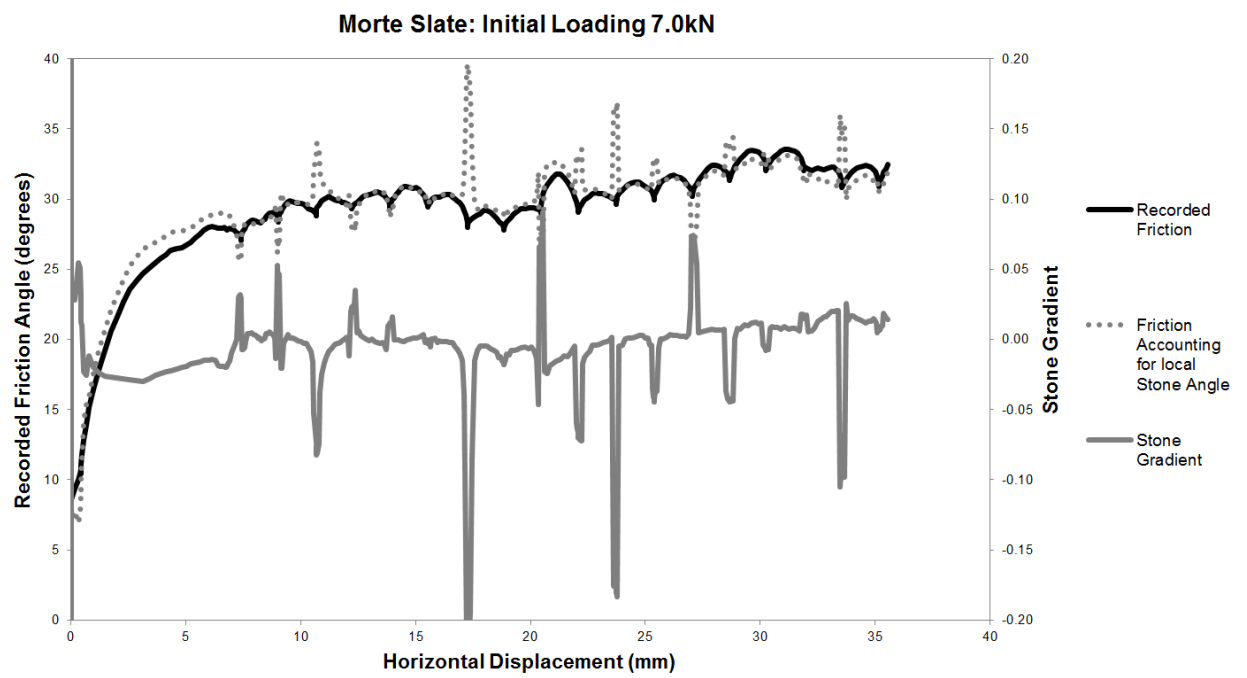
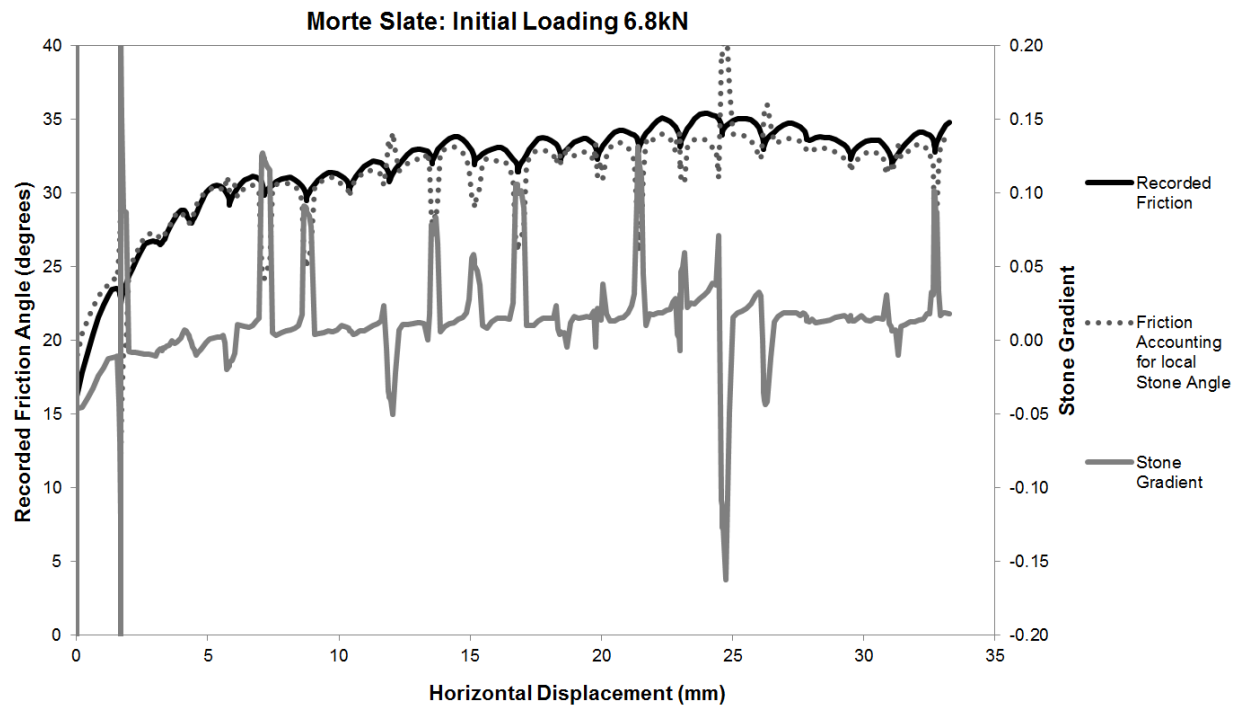


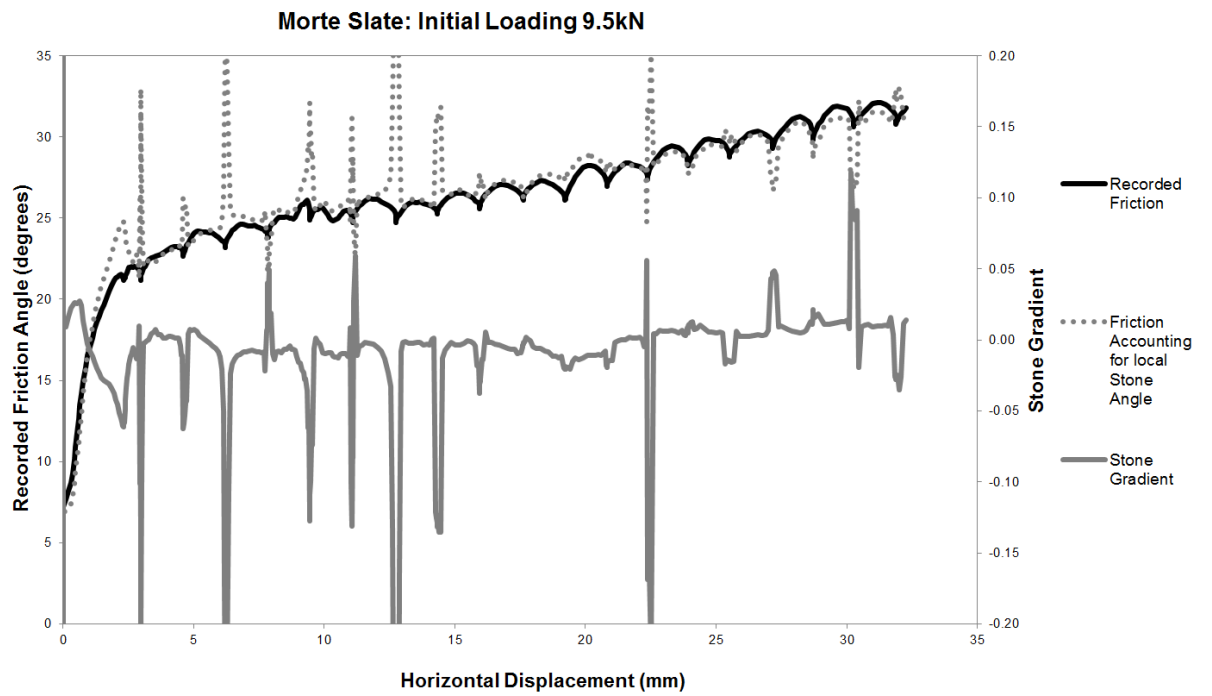
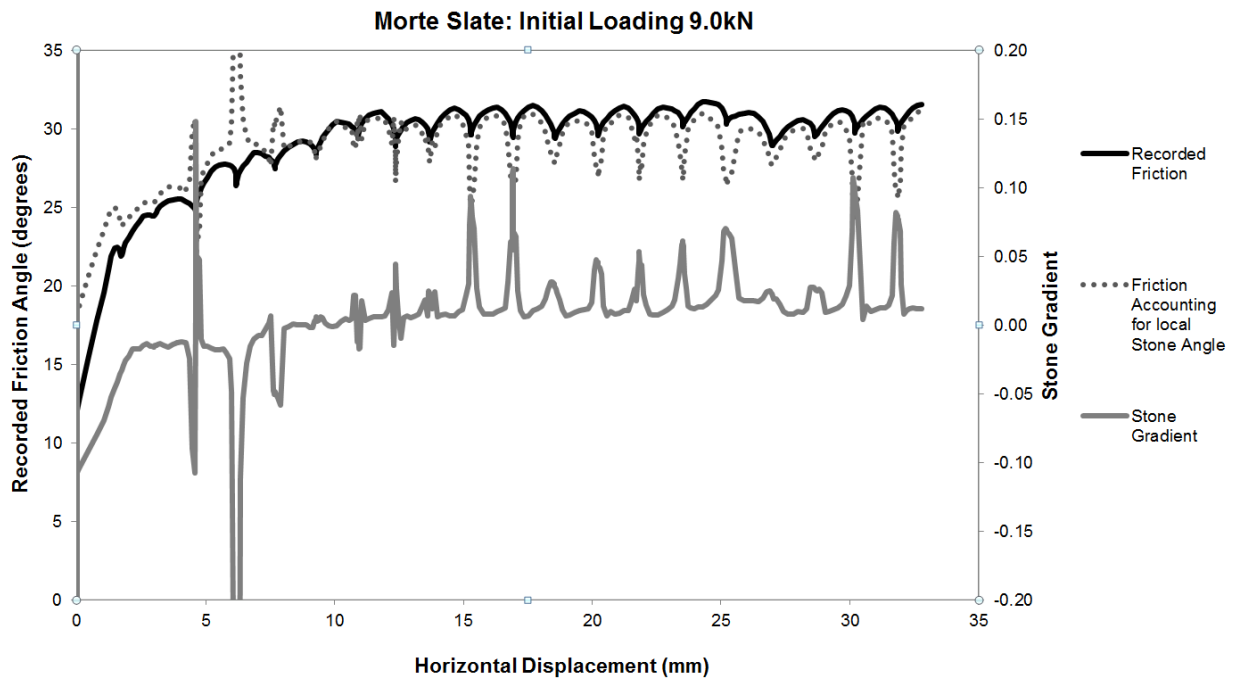
A3.1.3 Morte Slate







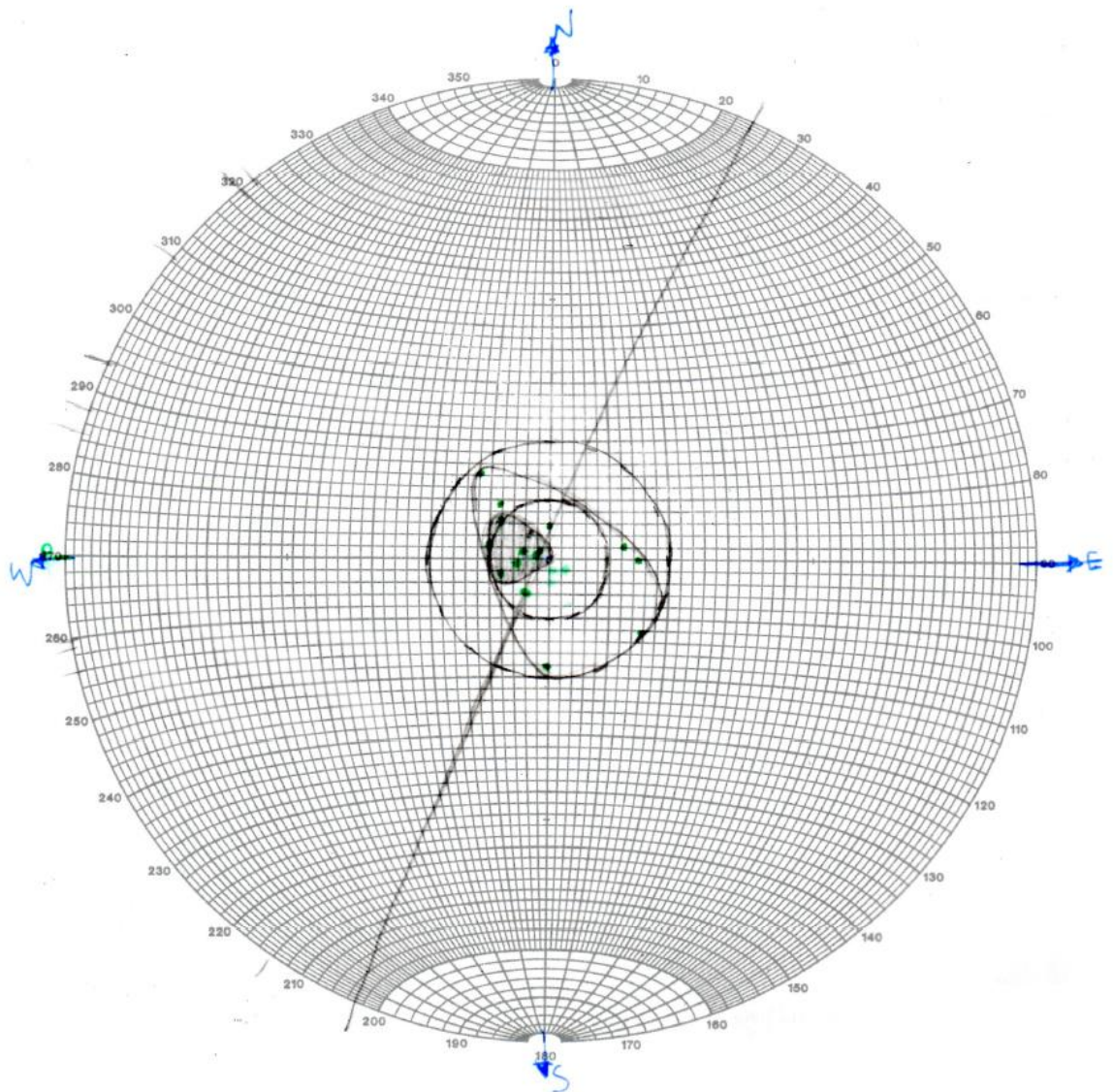
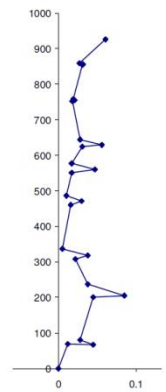




A3.2 Cotswold Wall Investigation

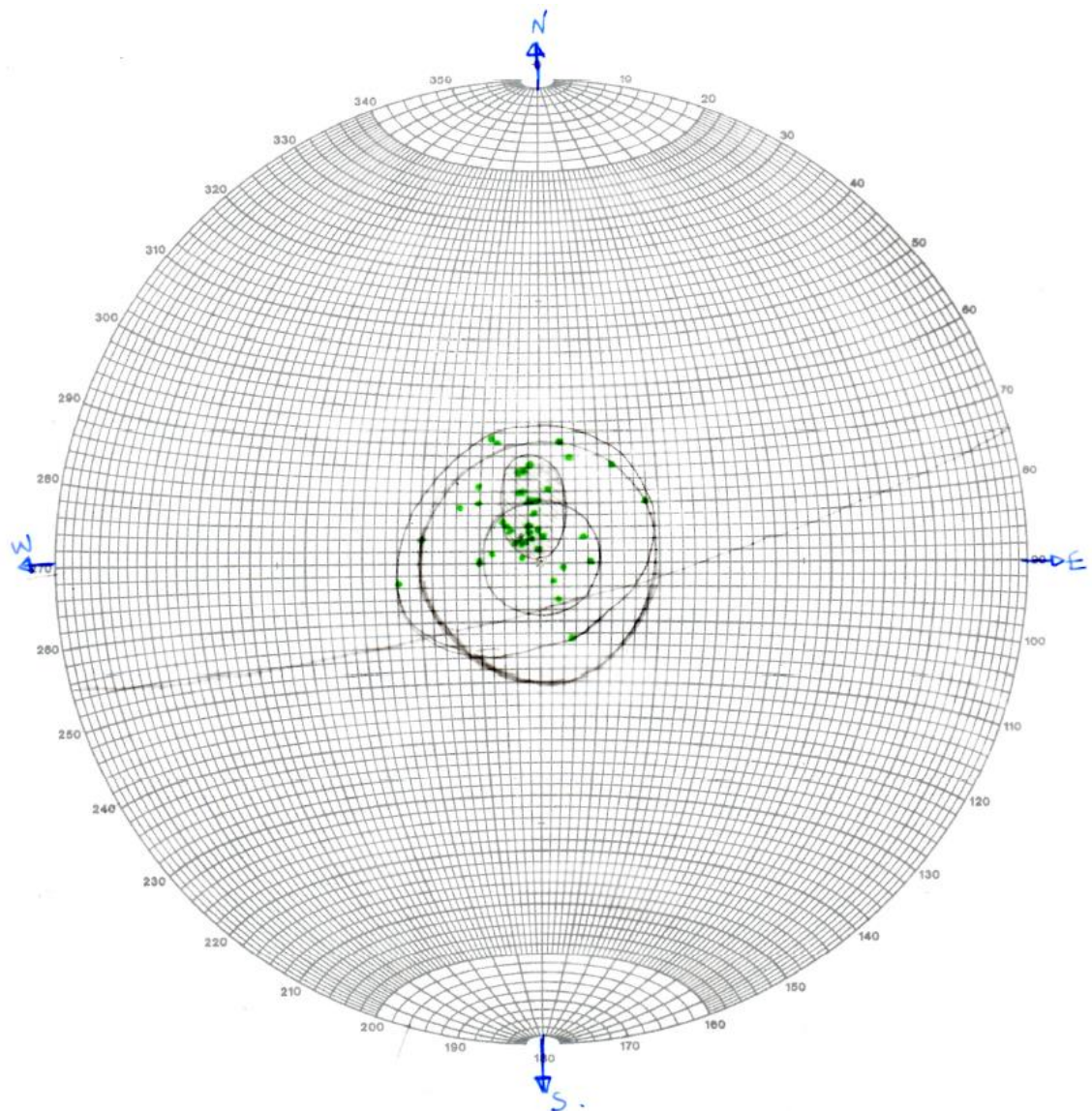
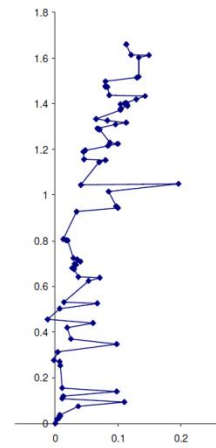
Batheaston Wall

Single face construction
Garden retaining wall
New build wall using reclaimed stone
Hard sandstone type stone
Wall height: approximately 1m
Average stone size: 0.02m^2
Wall Batter: 1°
Wall Bearing: 294°

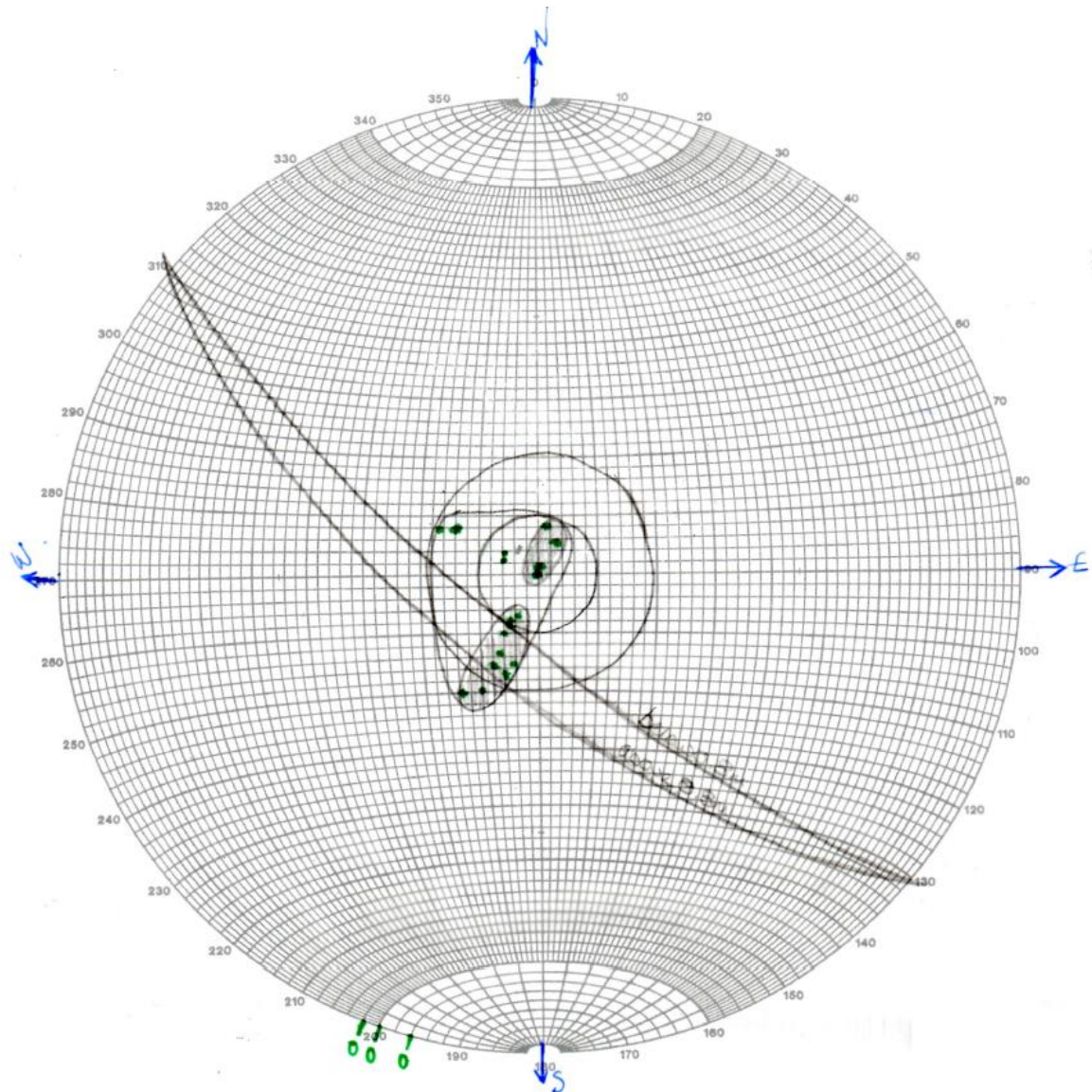
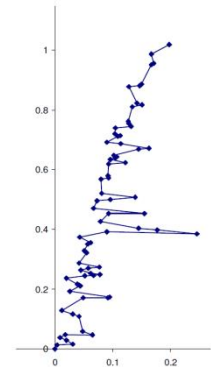


Northleach (Section 2 in Thermal Imaging Study)

Double face construction
Retains single carriage way road
Original construction
Cotswold stone
Wall height: approximately 2m
Average stone size: 0.022m^2
Wall Batter: 8°
Wall Direction: 165°

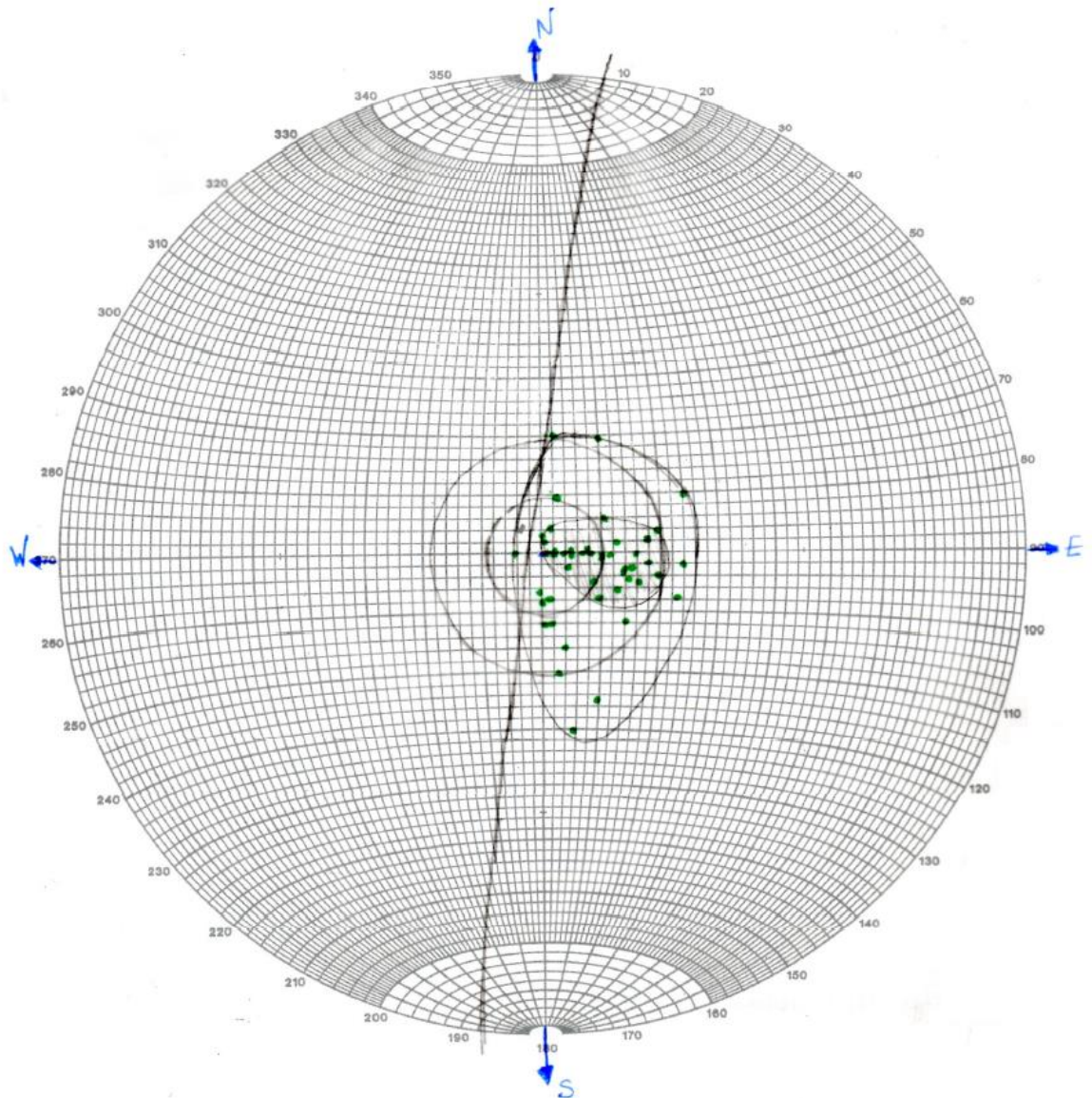
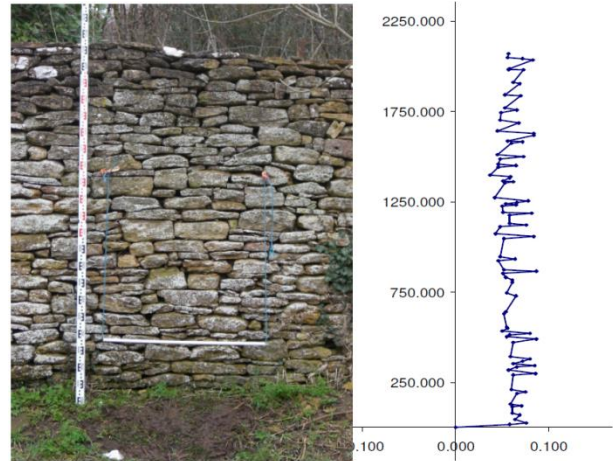


Unknown Construction
Ha-ha
Morte Slate from Hestercombe
Wall height: approximately 1.2m
Average stone size: 0.011m²
Wall Batter below 0.8m: 10°
Wall Batter above 0.8m: 18°
Wall Direction: 220°



Norton St Phillip

Likely double faced construction
 Field Boundary Wall
 Local Hard Sandstone and Shelley Lime
 Wall height: approximately 2.2m
 Height includes 0.65m parapet
 Average stone size: 0.013m²
 Wall Batter: 2°
 Wall Direction: 288°

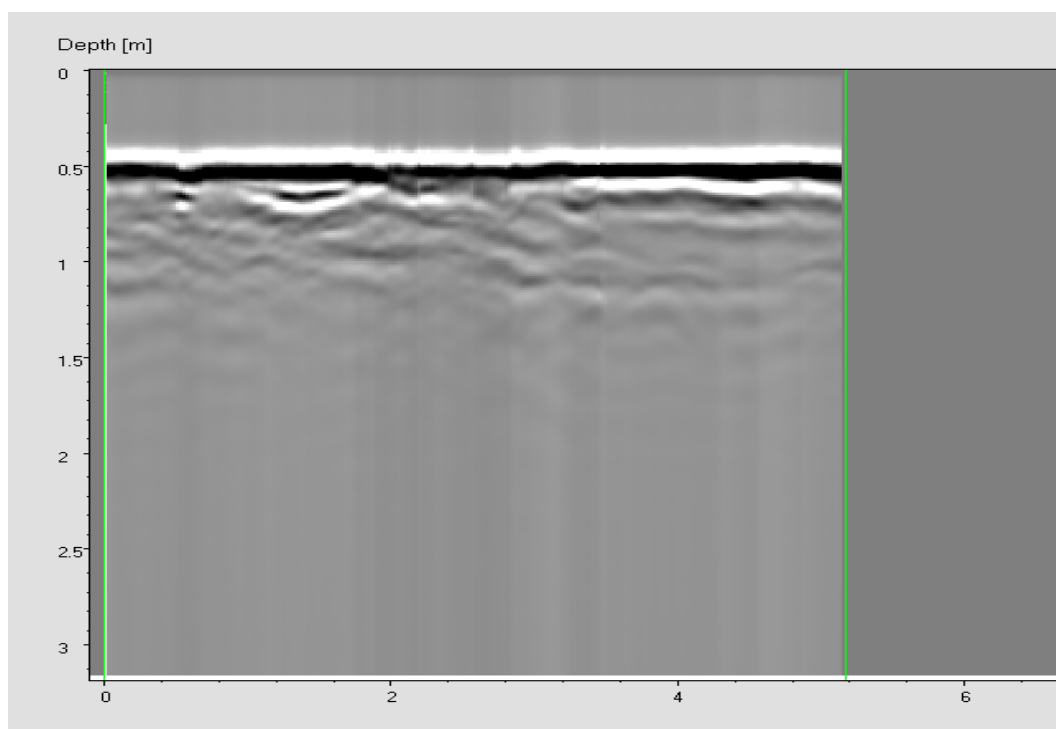


Appendix 4

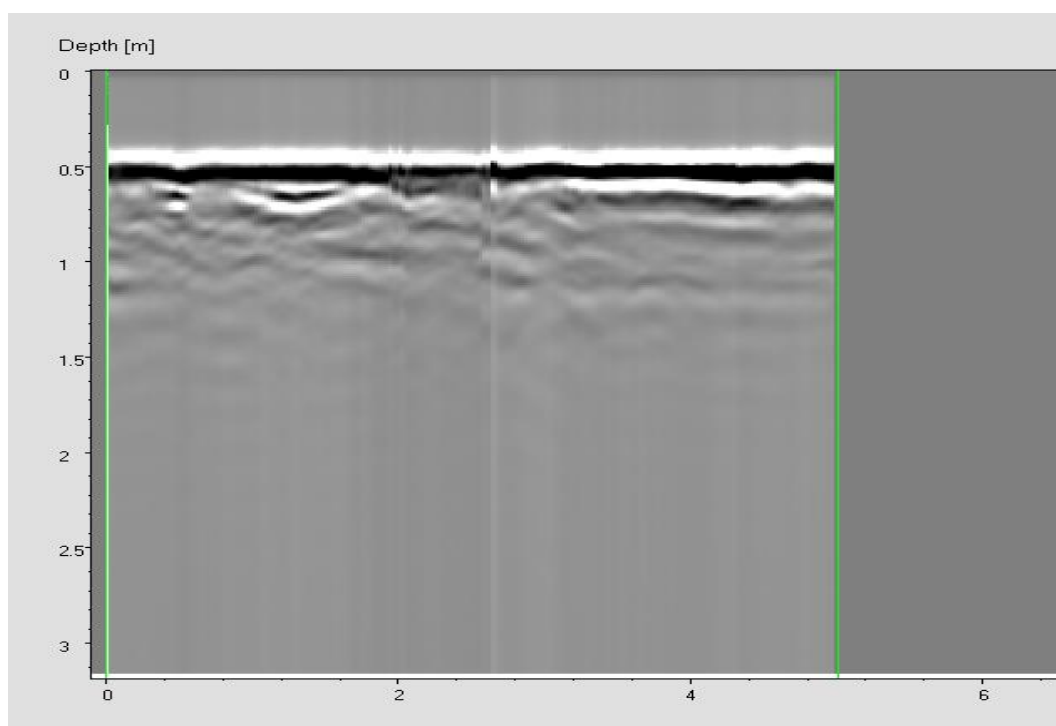
Geophysics

This appendix contains the GPR images for all the scans carried out both above the wall and at the wall face. Each scan location was repeated 3 times and consistency was shown between the scans as can be seen in the images below. Some of the features seen are explored in Chapter 6.

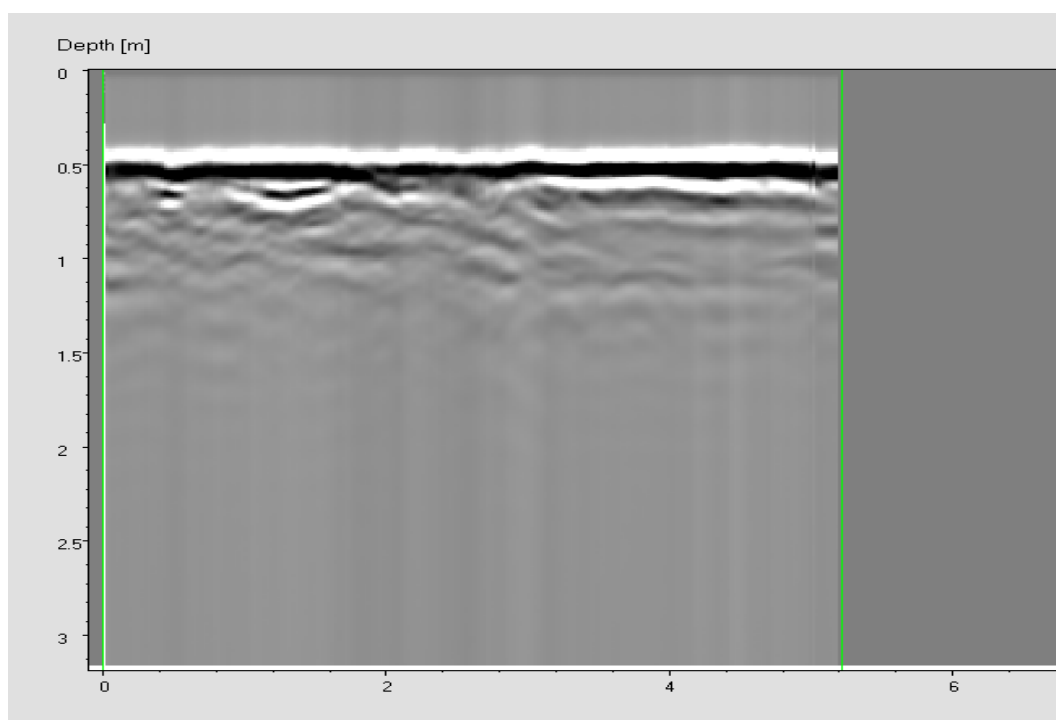
A4.1 Scans immediately behind face



Repeat 1

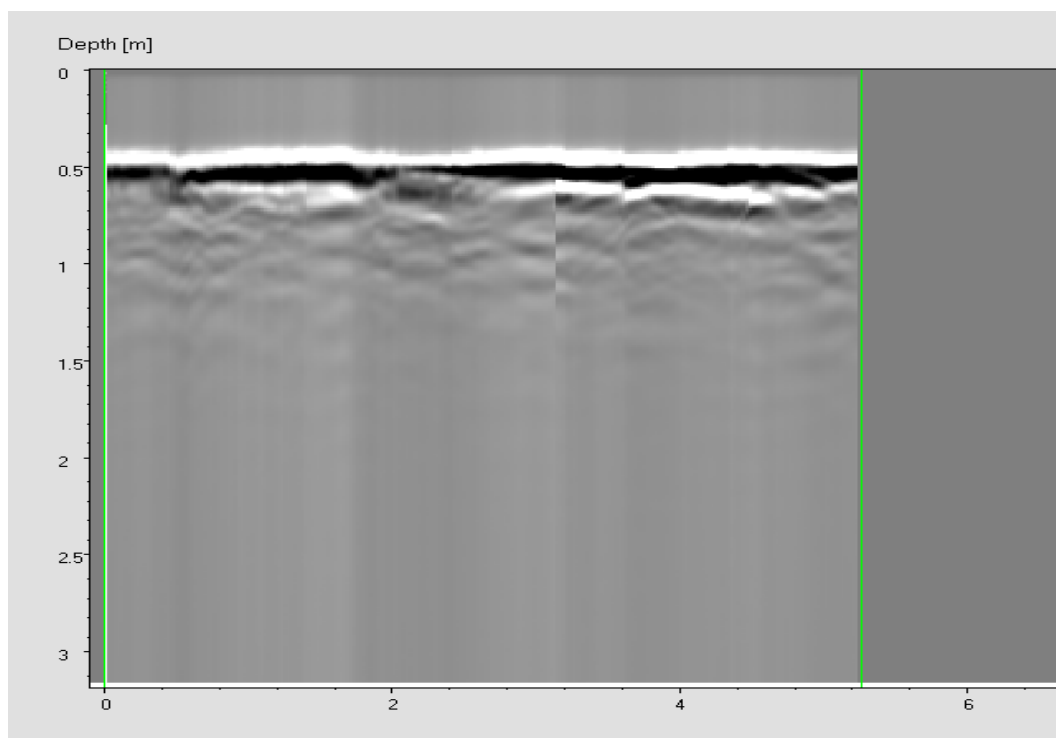


Repeat 2

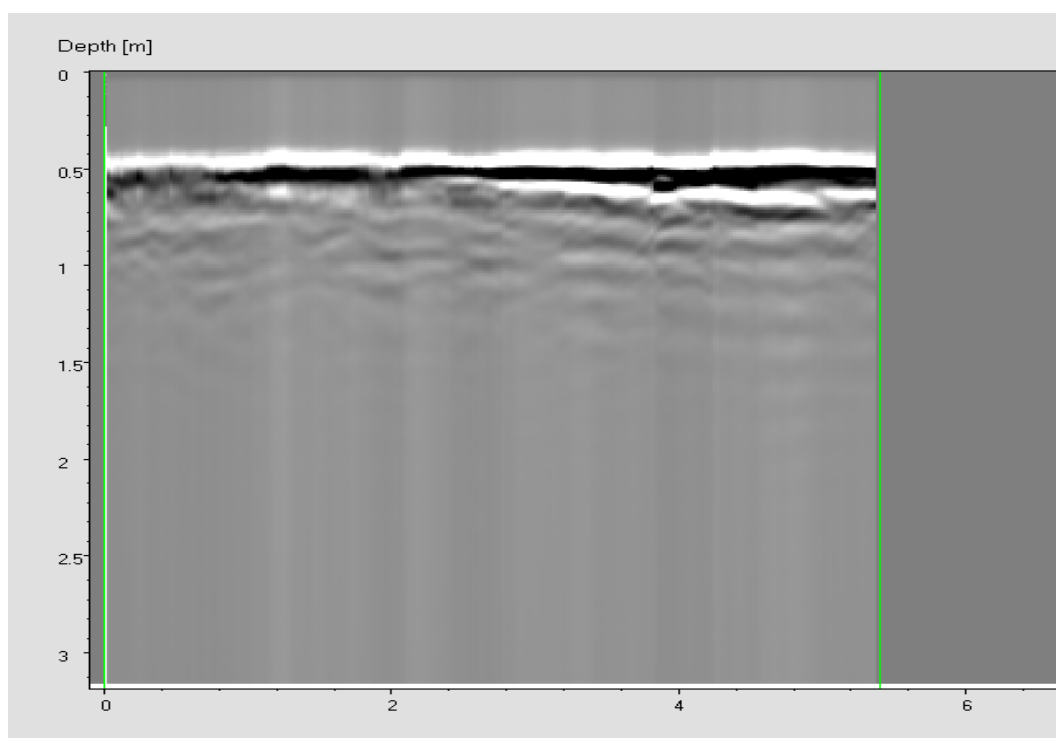


Repeat 3

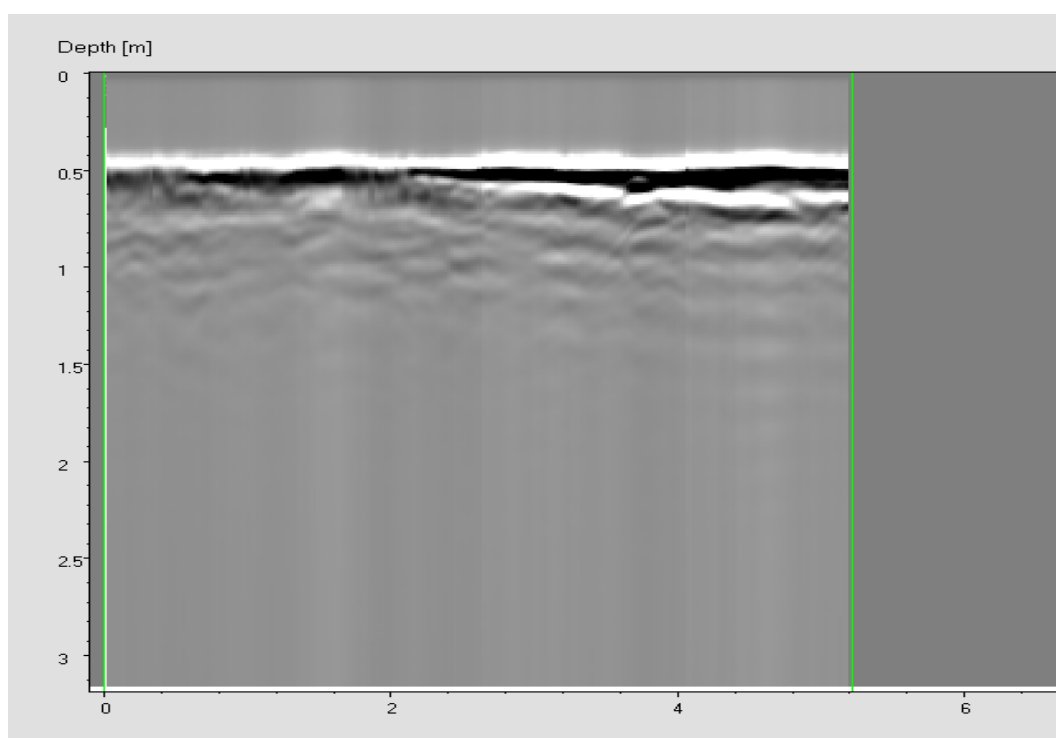
A4.2 Scans 0.5m behind face



Repeat 1

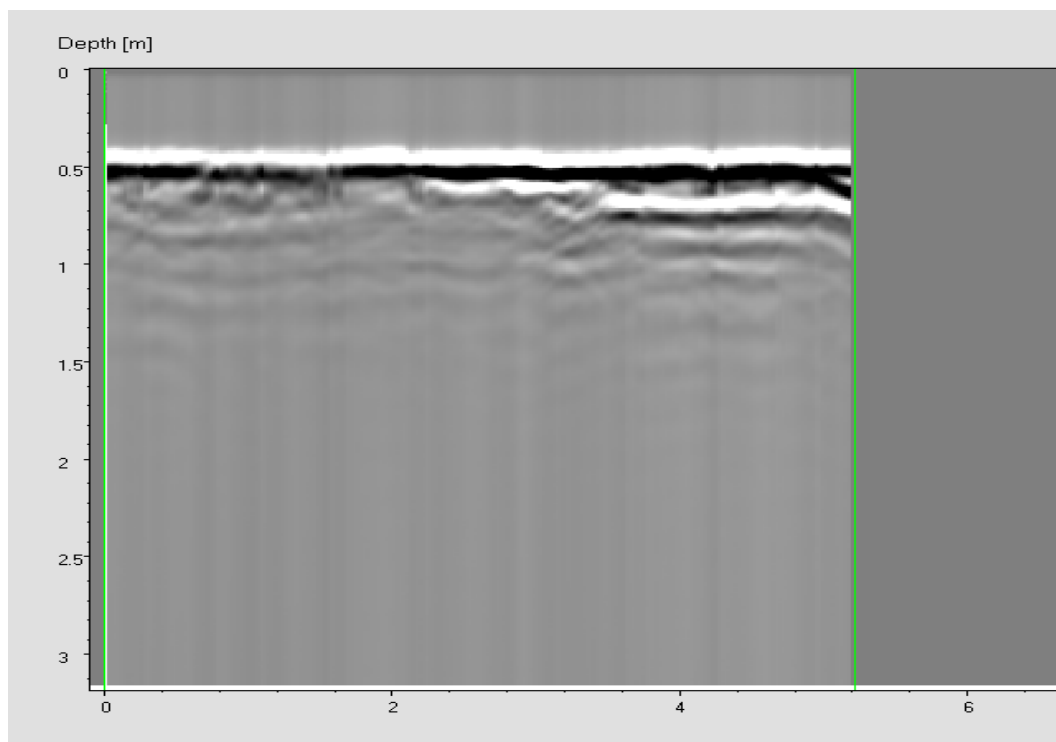


Repeat 2

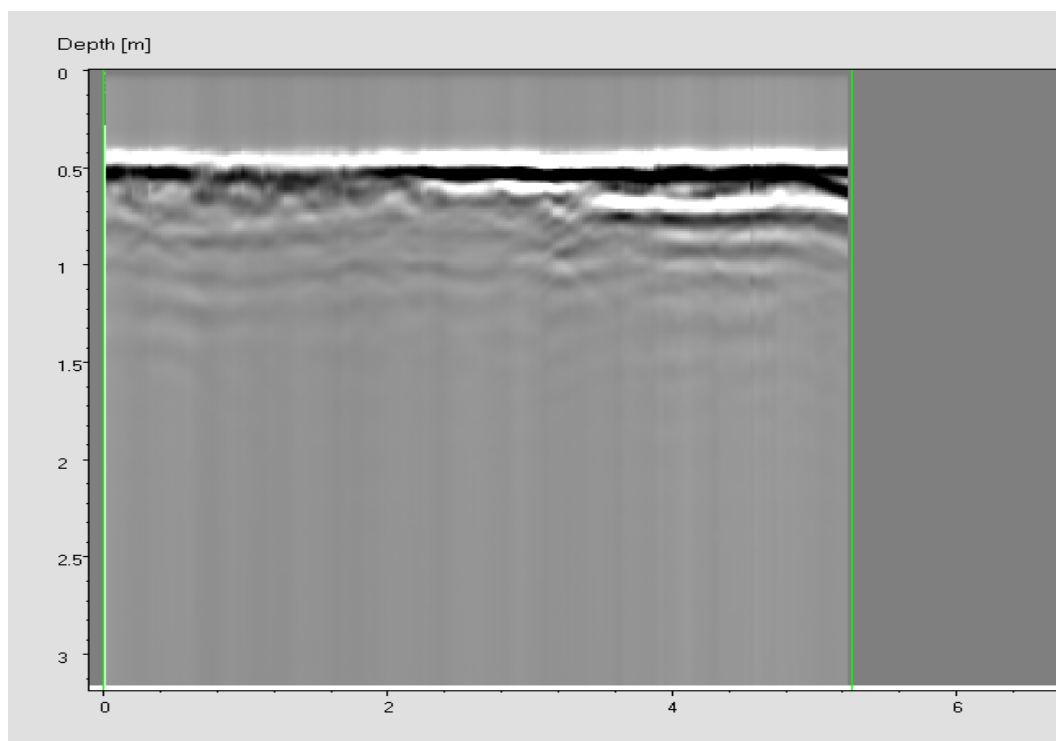


Repeat 3

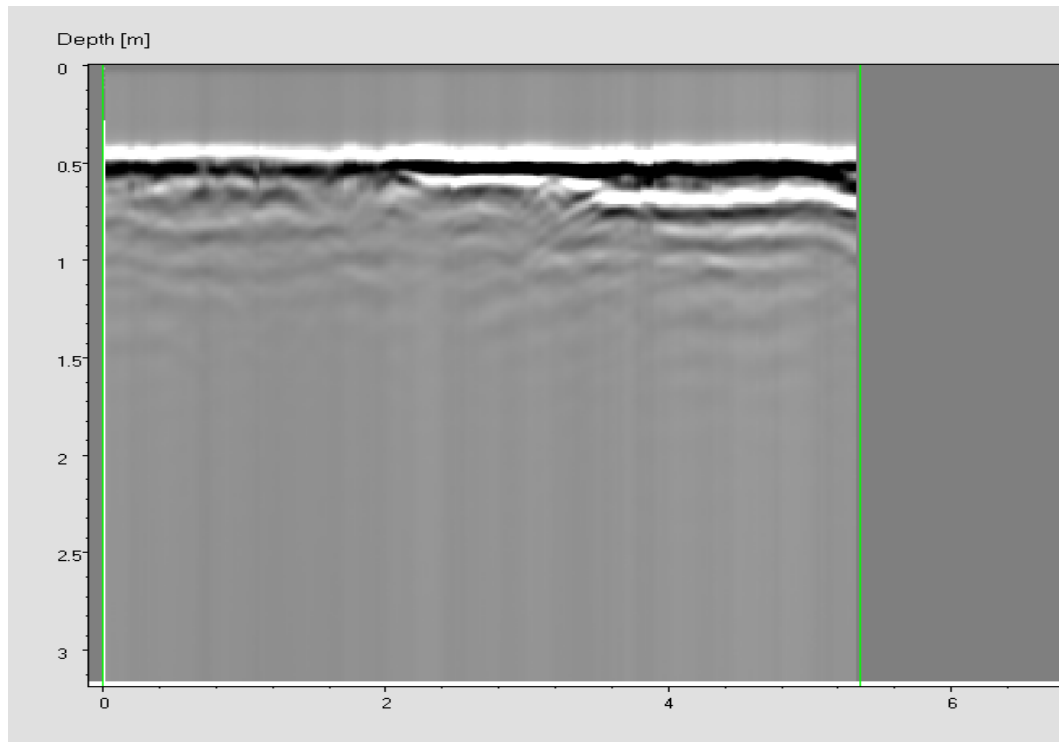
A4.3 Scans 1m behind face



Repeat 1

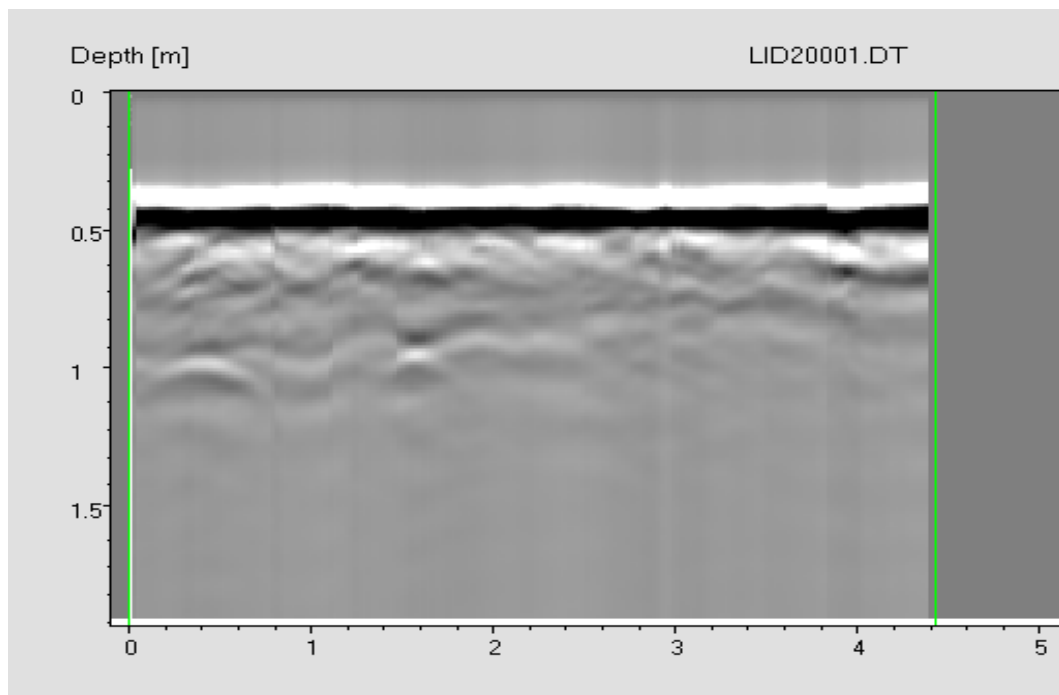


Repeat 2

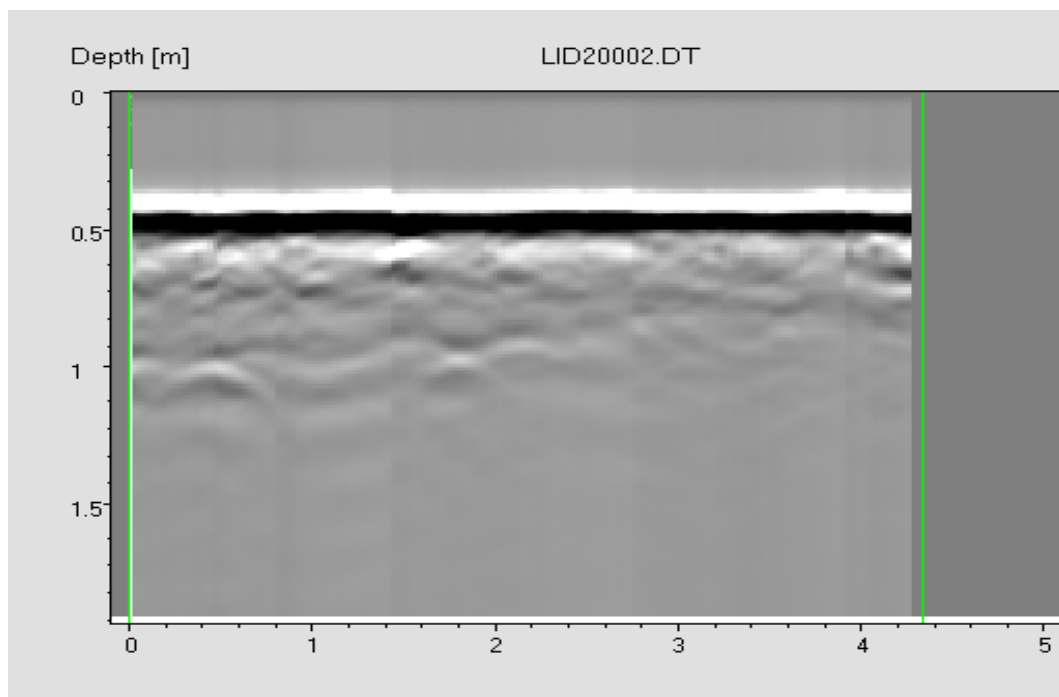


Repeat 3

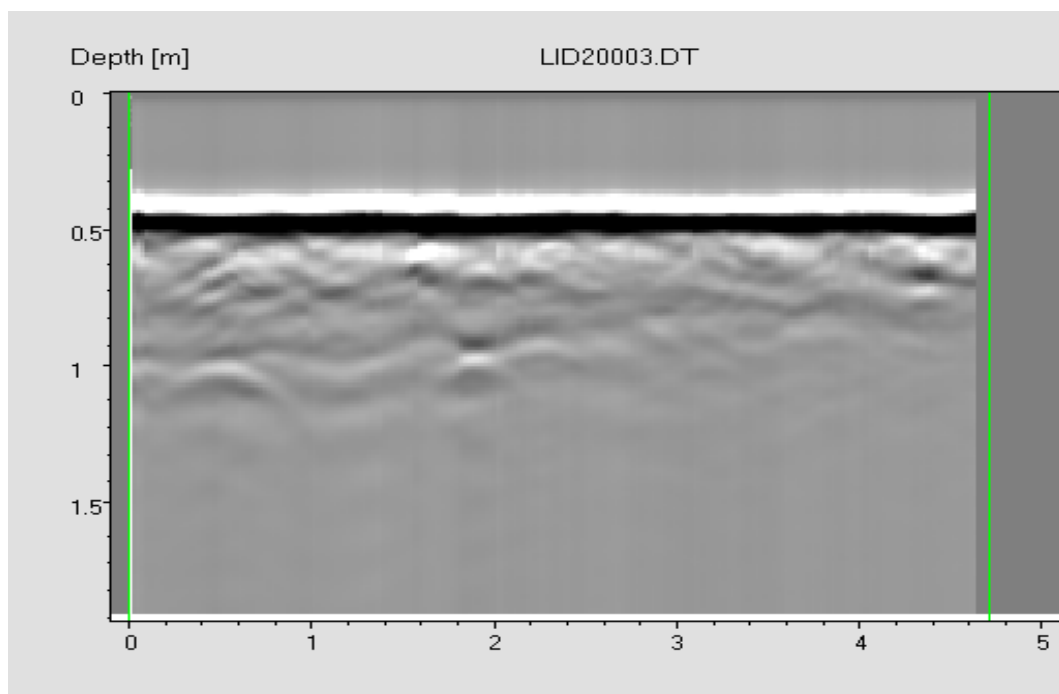
A4.4 Scans to top of wall face



Repeat 1

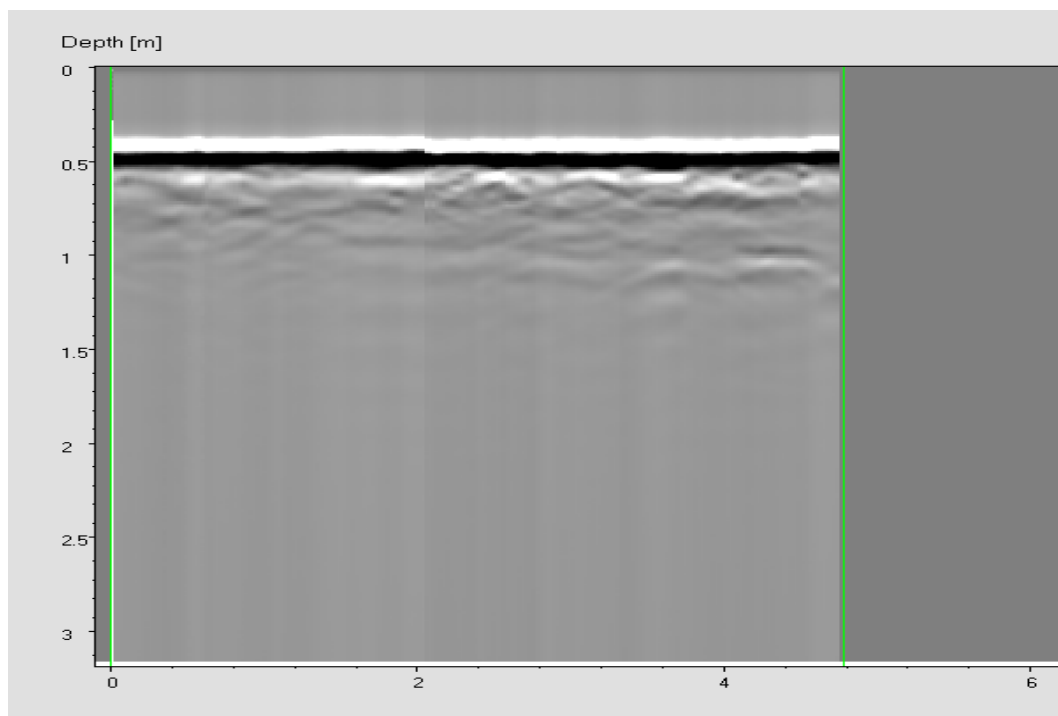


Repeat 2

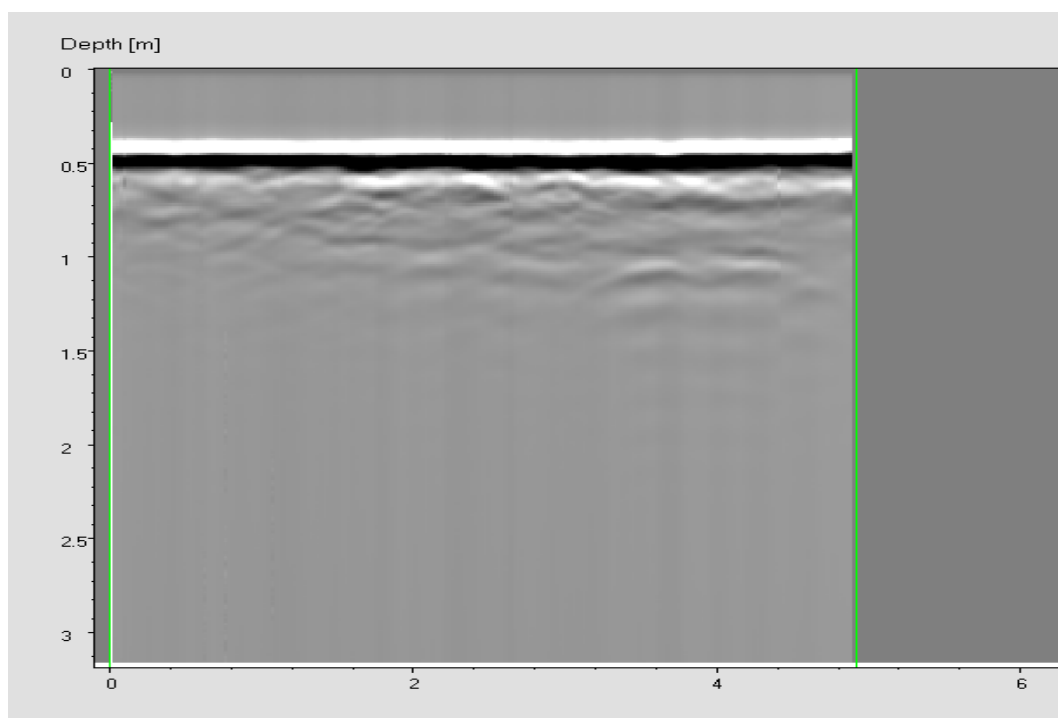


Repeat 3

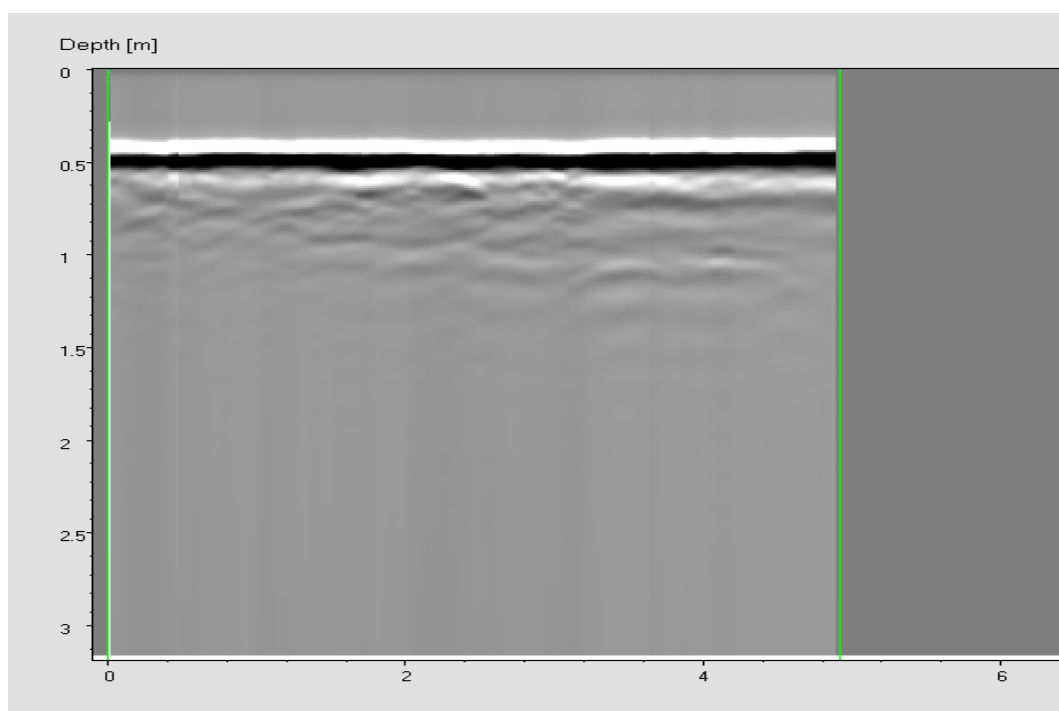
A4.5 Scans to bottom of wall face



Repeat 1



Repeat 2



Repeat 3

Appendix 5

Thermal Images

A5.1 Northleach Thermal Investigation Images

A full set of thermal images from an initial 24hr investigation at Northleach, Gloucestershire, from 06/06/13 to 07/06/13.

A5.2 Additional Thermal Images of French Construction

Additional images taken in September 2013 in the Cévennes area of France.

A5.3 Additional WUFI Data

Additional figures for East, West and North facing simulations as provided for South facing simulations in main body of text.

A5.1 Northleach Thermal Investigation Images

A5.1.1 Section 1

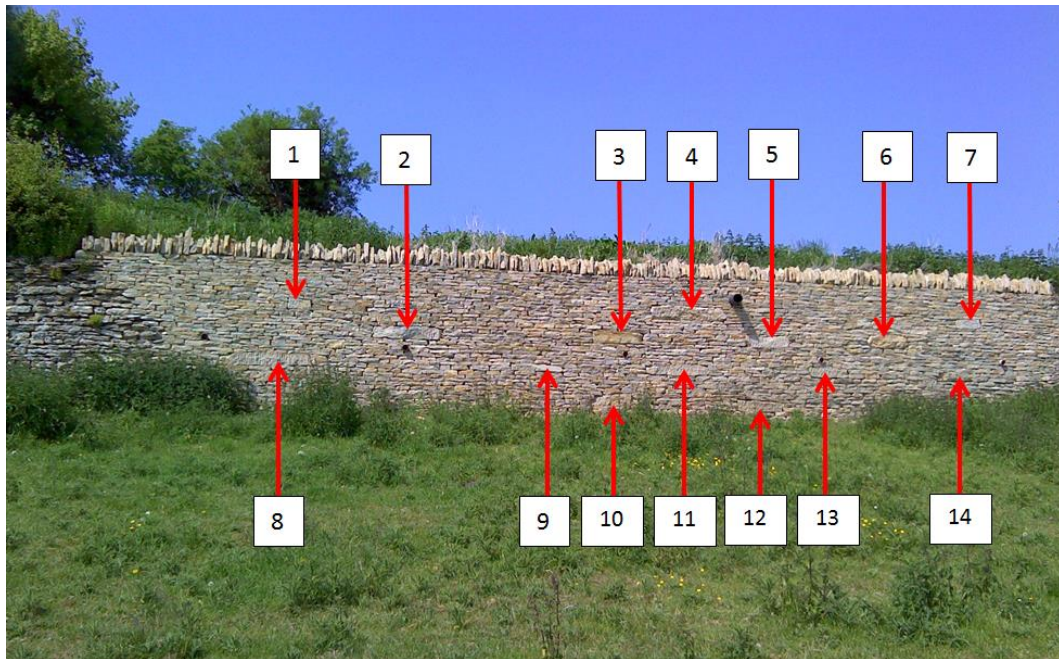
A5.1.2 Section 2

A5.1.3 Section 3

A5.1.4 Section 4

A5.1.5 Sections 5 and 6

A5.1.1 Section 1:



Visual image with all through stones highlighted Stone numbers replicated on thermal images below.

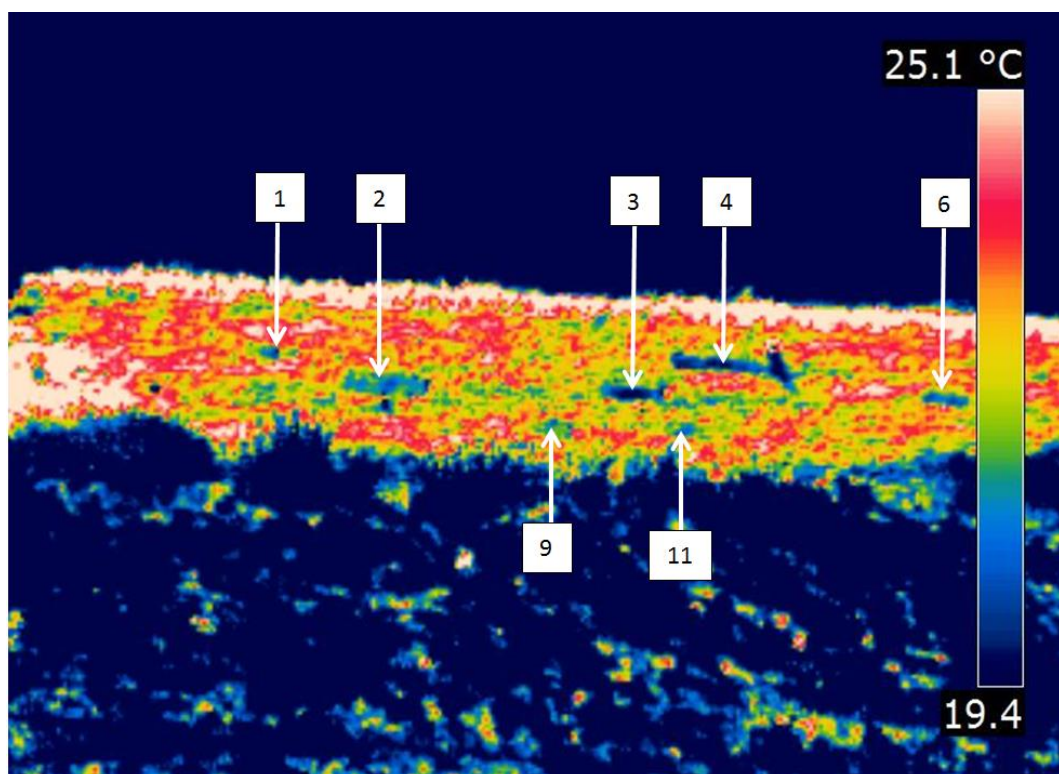


Image taken: 15:00 06/06/13; Through stones 2, 3, 4&6 are obvious in both the thermal and visual images. Through stones 1, 2&3: indications of their presence may be seen in the thermal image by areas that appear slightly cooler than the surrounding stone, however without confirmation from the visual image it could not be defiantly said these are though stones from the thermal image alone.

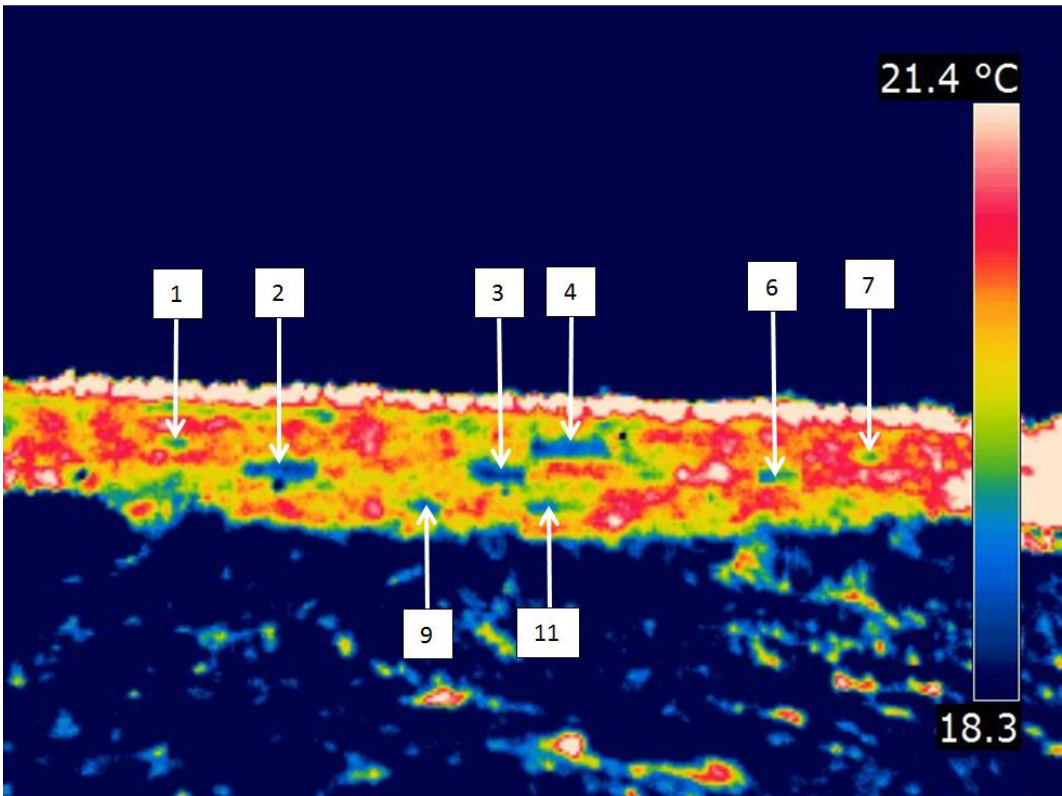


Image taken: 17:30 06/06/13; 8 through stones visible

Image from 20:00 06/06/13 in main body of thesis

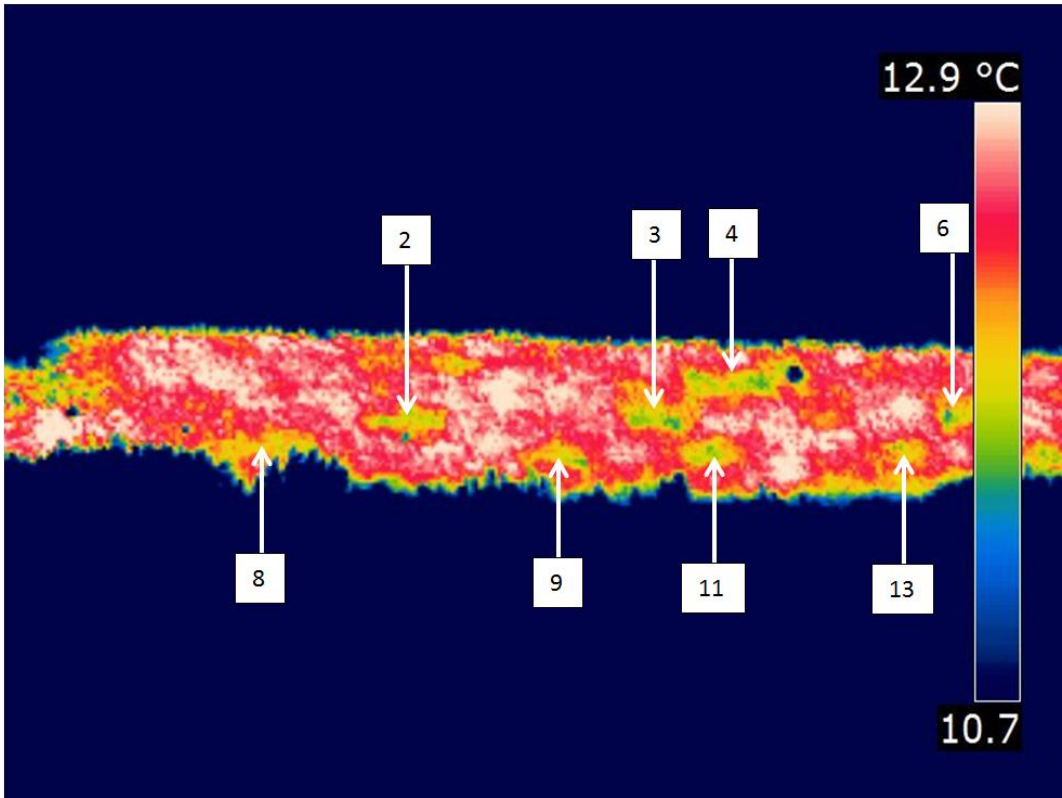


Image taken: 22:00 06/06/13; 8 though stones visible.

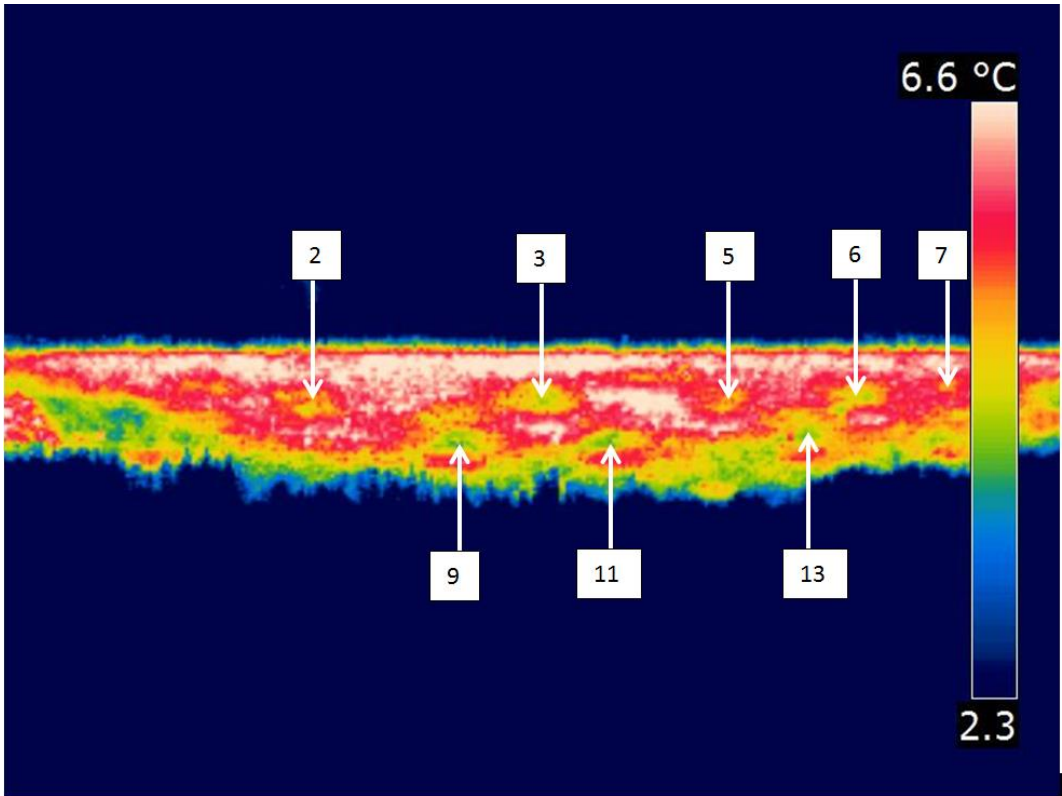


Image taken 05:30 07/06/13; 8 though stones visible

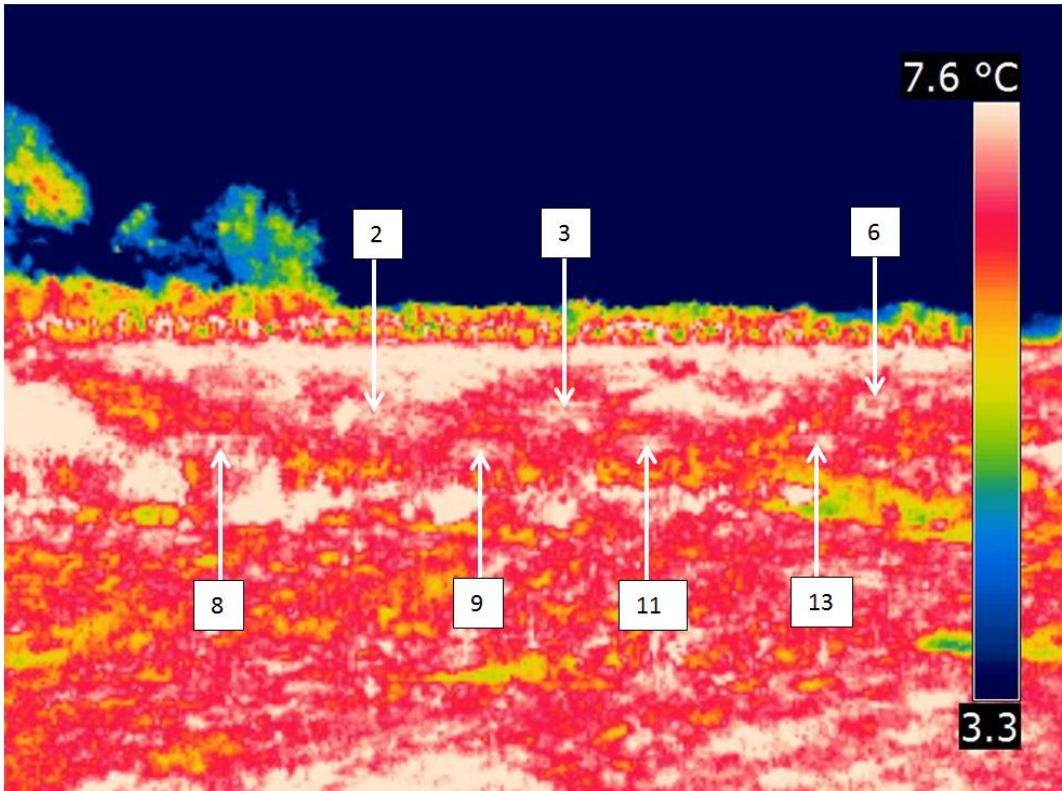


Image taken: 08:00 07/06/13; 7 though stones visible, however the temperature differences are small and they are not immediately obvious.

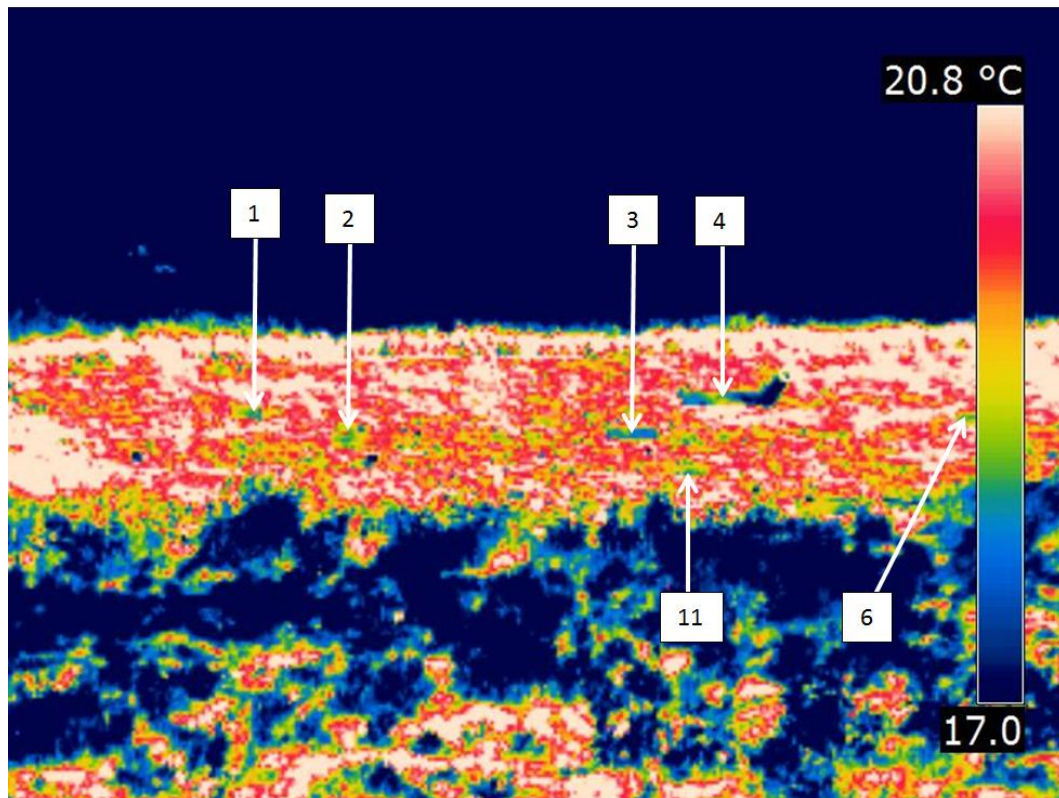


Image taken: 10:30 07/06/13; through stones 3&4 most obvious, stones 1, 2, 6&11 partially visible when compared to visual image. At this time a wide variety of temperatures can be seen across all the stones in the wall.

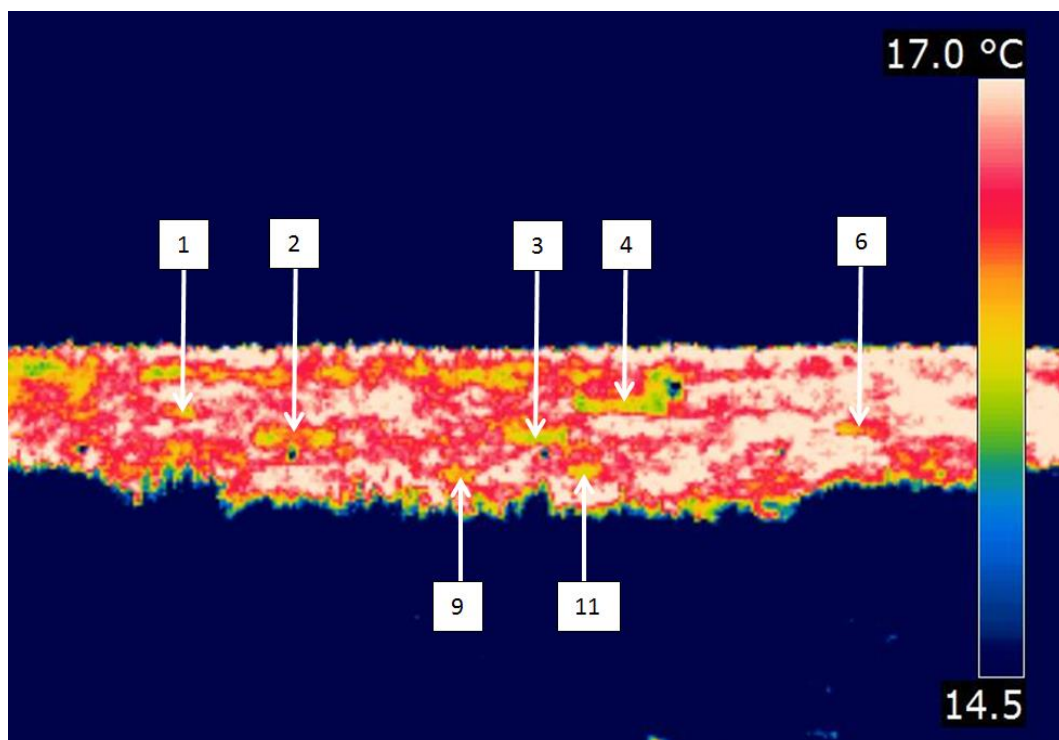


Image taken: 13:00 07/06/13; 7 though stones visible. At this time a number of areas can be seen with a similar temperature to the through stones. Therefore care needs to be taken when interpreting thermal imaging results.

A5.1.2 Section 2



Visual image: Section 2, visible features include weathering of face, a small alcove and vegetation growth near top of wall.

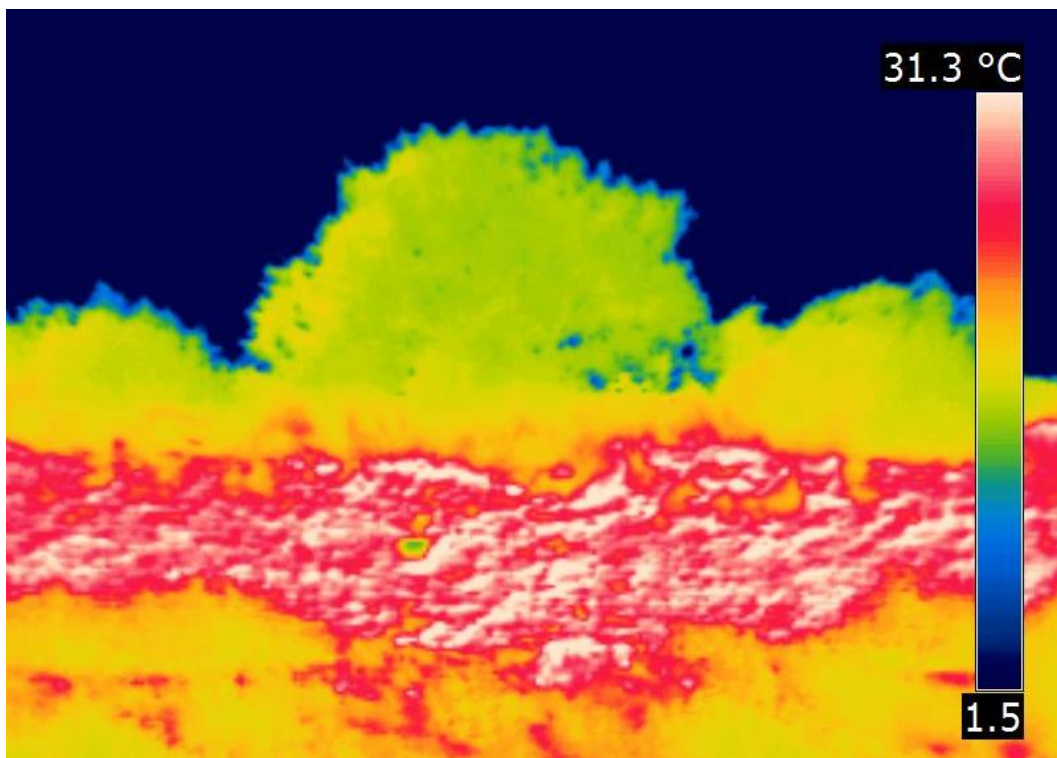


Image taken 15:00 06/06/13; wall face shows relatively uniform temperature. Significantly cooler areas correspond to small alcove and vegetation at wall face. Small variations in temperature across face likely due to the uneven surface due to weathering.

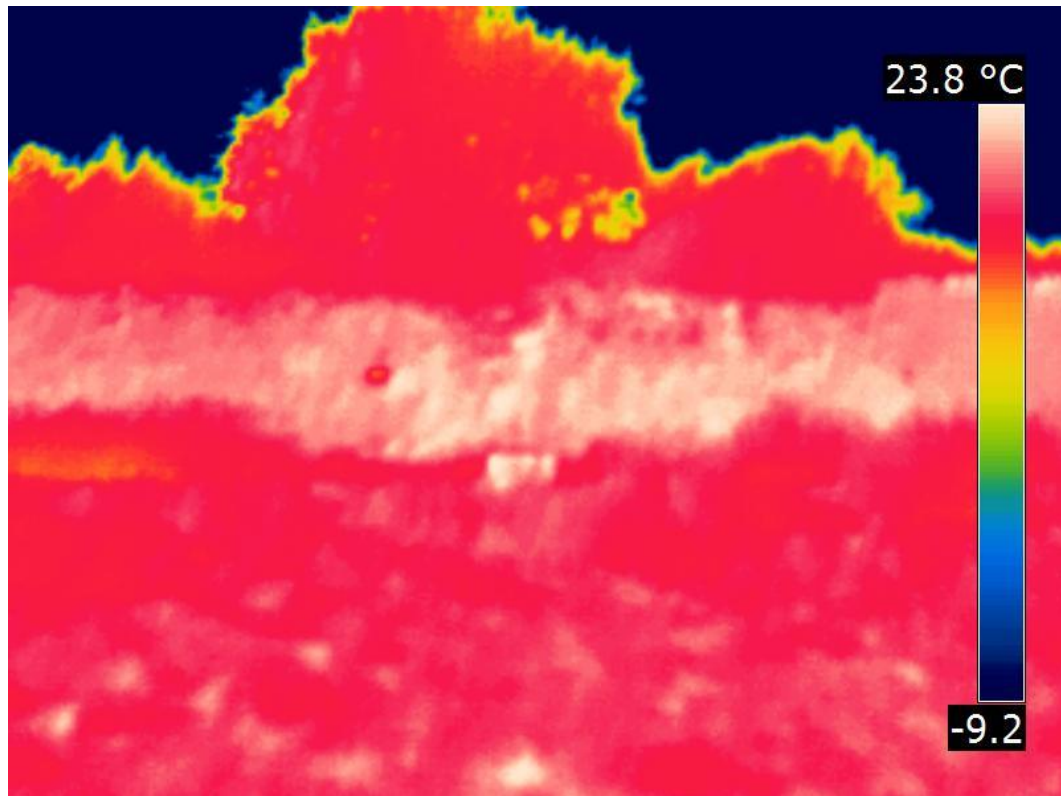


Image taken 17:30 06/06/13; image not in focus therefore little information to be gained.

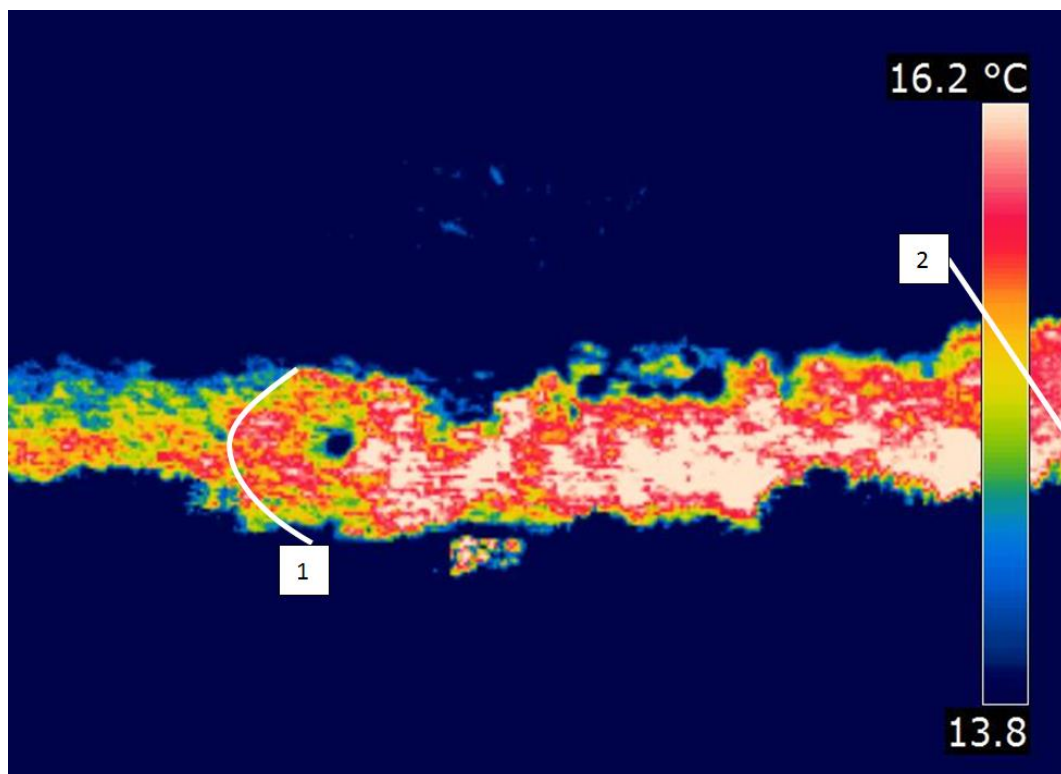


Image taken 20:00 06/06/13; where vegetation is present at the top of the wall it can be seen to be significantly cooler. Along 1&2 changes in temperature can be seen where construction changes.

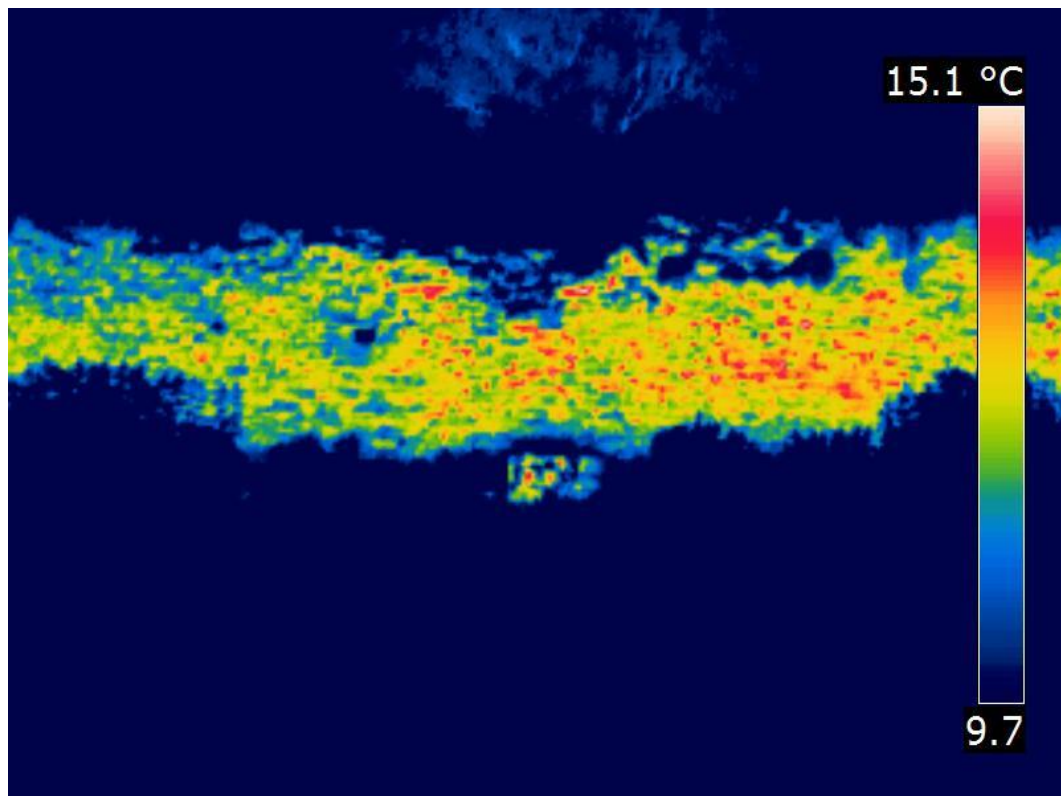


Image taken 22:00 06/06/13: wall shows relatively constant temperature across face.

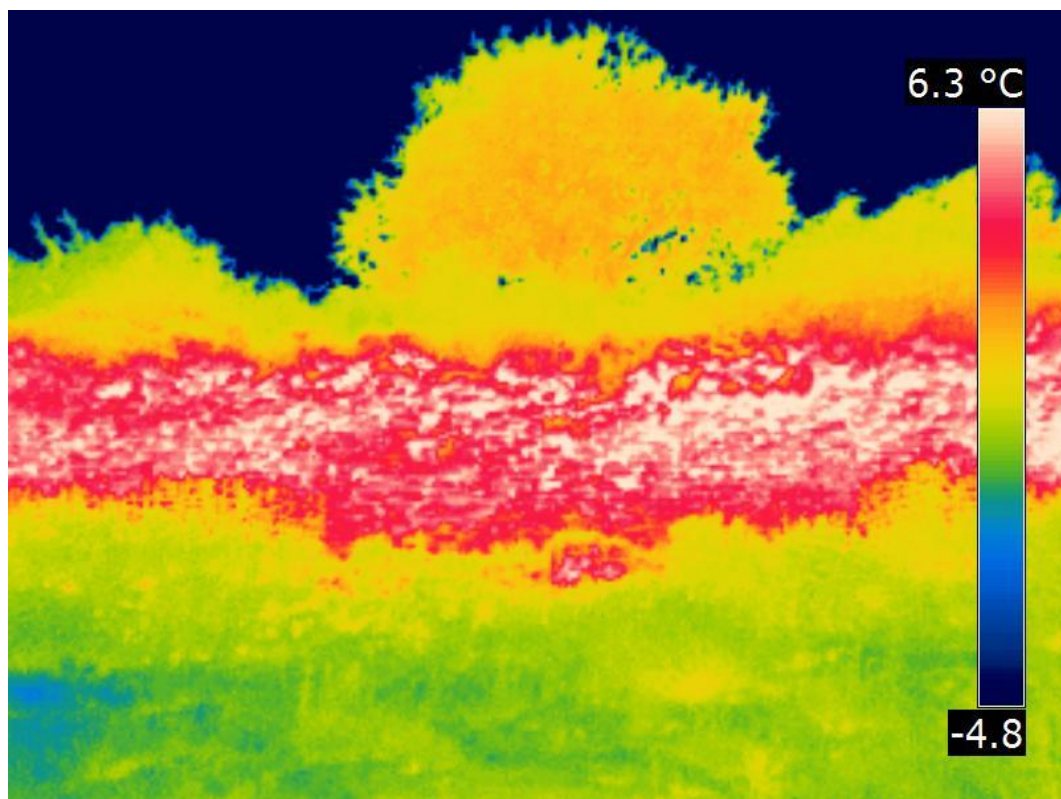


Image taken 05:00 07/07/13; individual stones across the wall face can be identified, possibly do to the wider joints in this area compared to other wall sections.

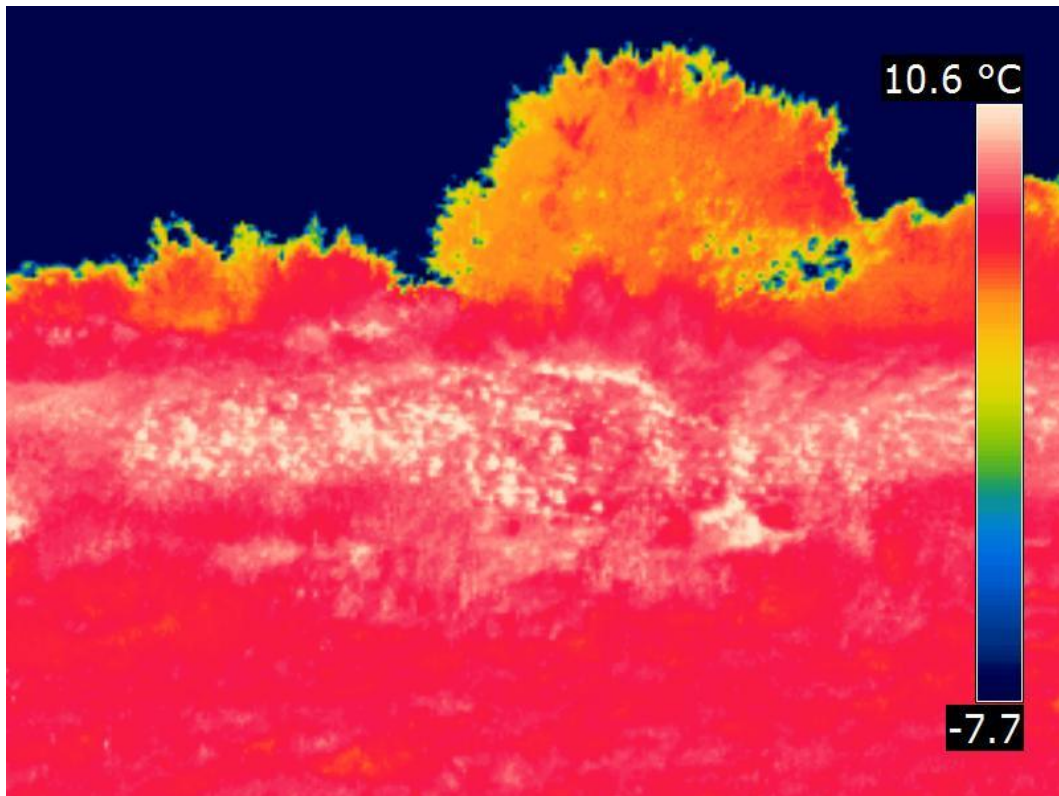


Image taken 08:00 07/07/16; as at 05:30 the individual stones within the wall can be identified in the thermal image

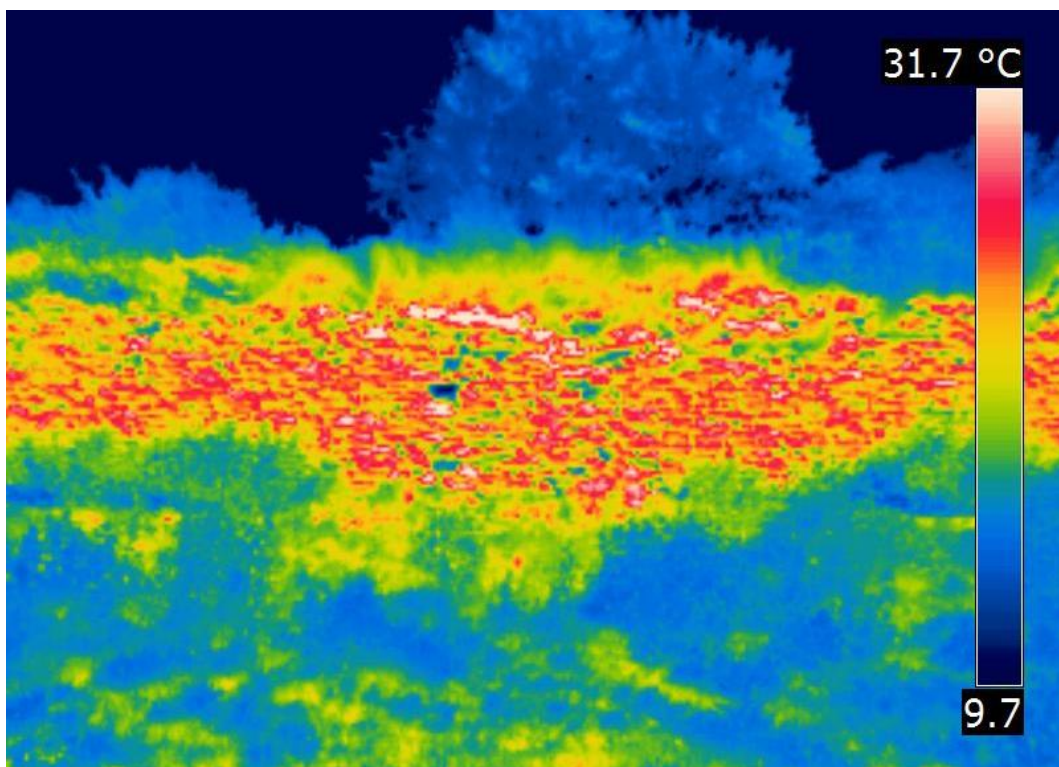


Image taken: 10:30 07/06/13; cooler areas of stone can be seen, these appear to correspond to areas of more severe weathering where the stone faces are set back from those around them.

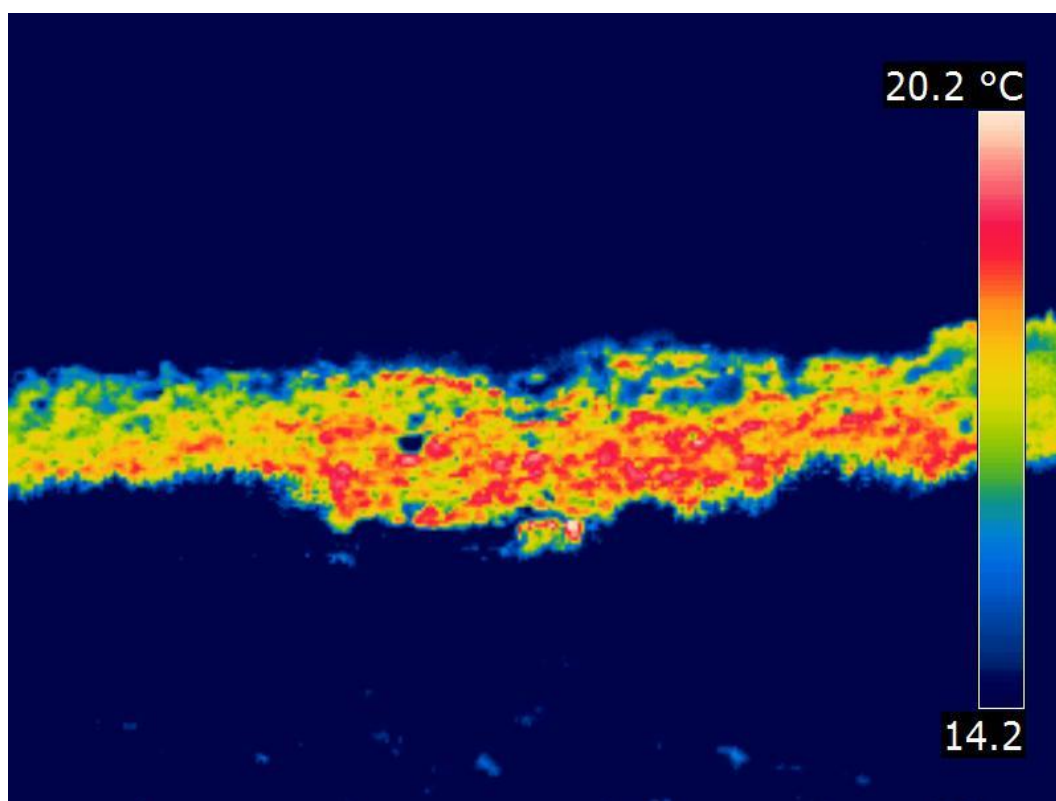


Image taken 13:00 07/07/13; image shows features similar to that seen at other times of day.

A5.1.3 Section 3



Visual image: 2 distinct areas of vegetation can be seen along with a buttress type feature to left of the section.

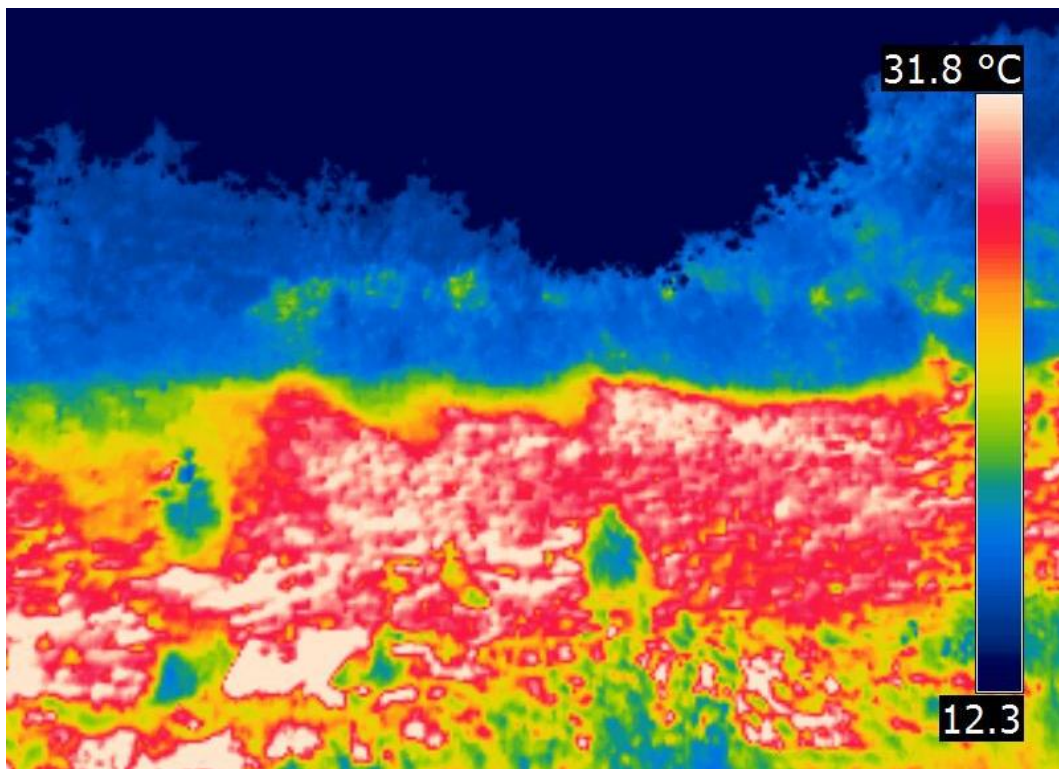


Image taken: 15:00 06/06/13; limited information to be gained from this image. Cooler section to top left of wall corresponds to shadowing vegetation above the wall at this time.

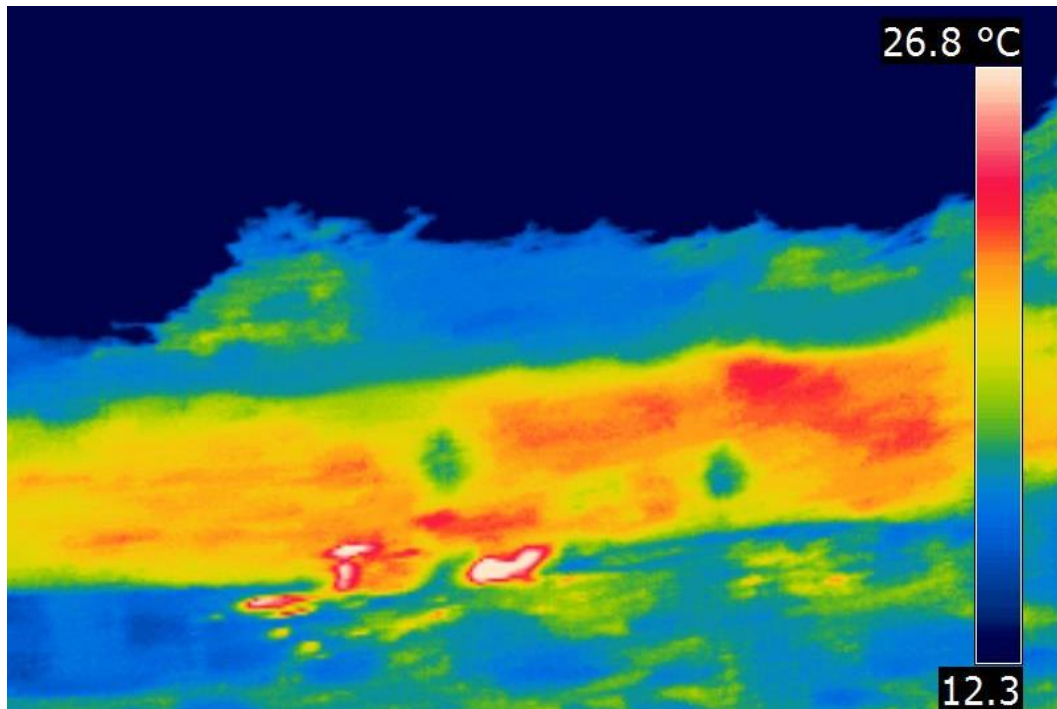


Image taken: 17:30 06/06/13; Image out of focus. However, the cooler area between the two areas of vegetation can start to be seen. Some temperature difference between the differing construction styles either side of this section can also be seen.

Image taken: 20:00 06/06/13; image in main body of thesis.

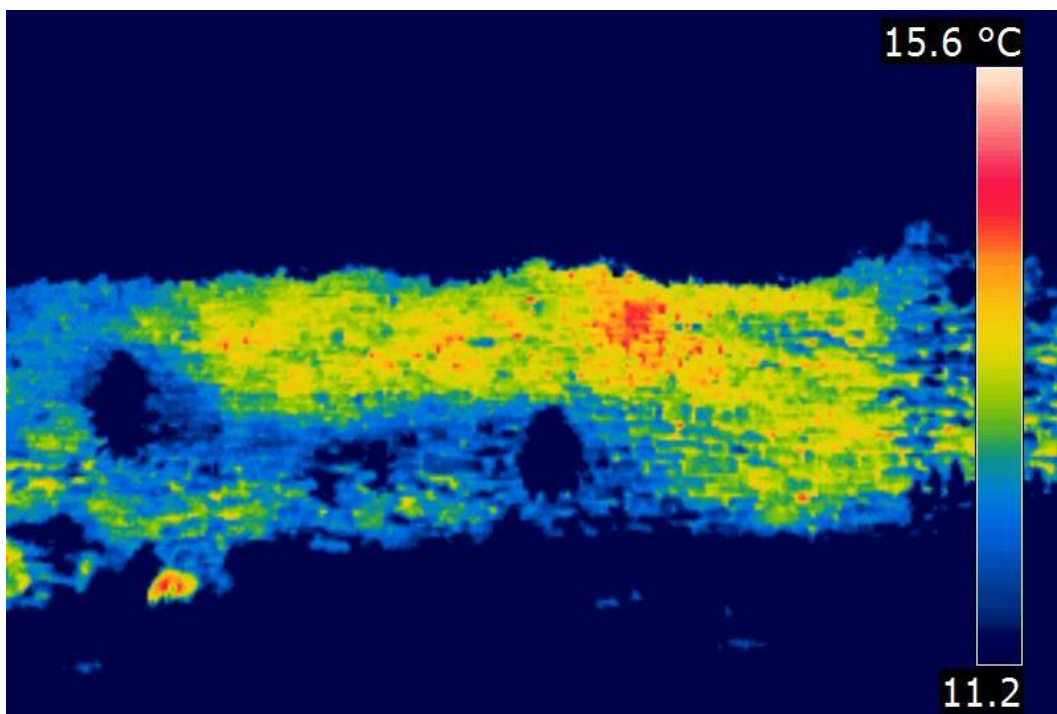


Image taken: 22:00 06/06/13; distinct cooler band between vegetation can be seen along with distinct temperature difference to construction style to the section to right of section 3.

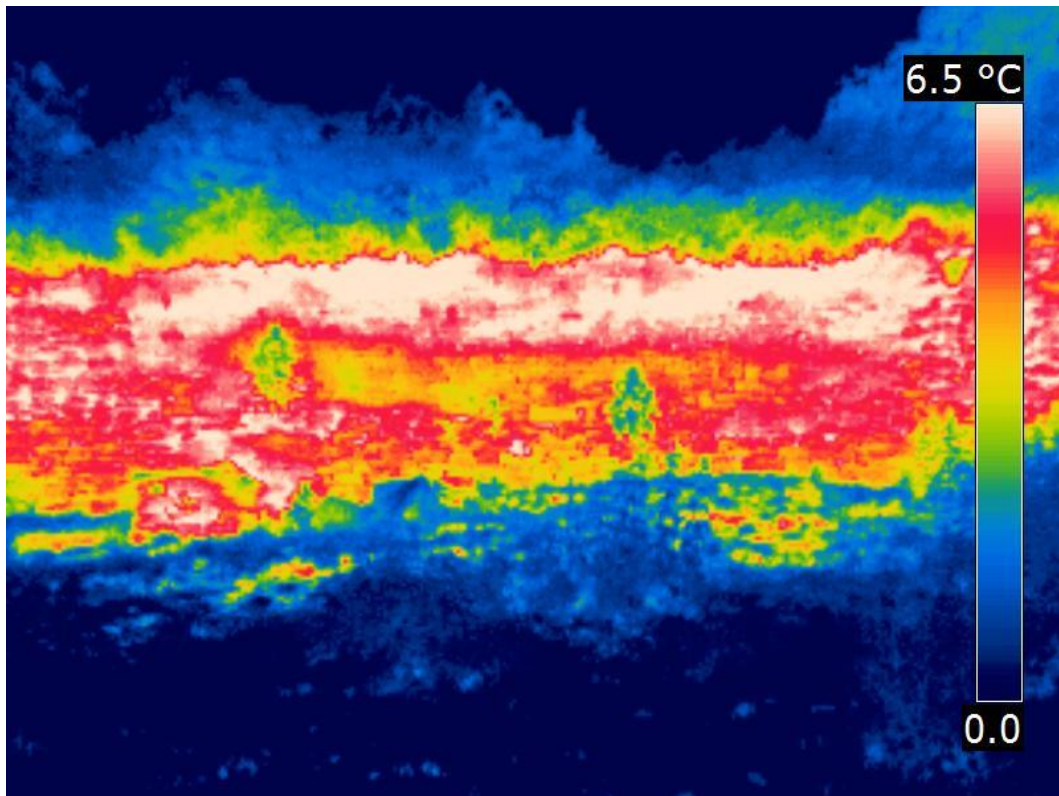


Image taken 05:30 07/07/13; Cooler band between two area of vegetation visible

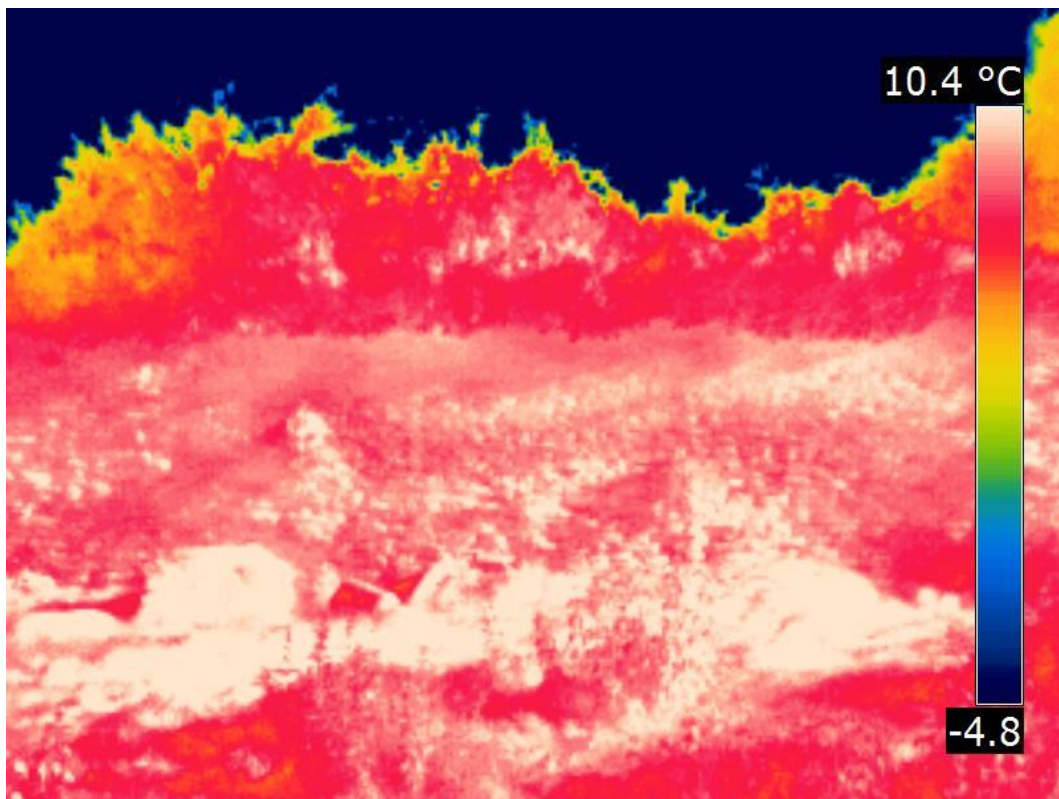


Image taken: 08:00 07/06/13; wall and surrounding area all at a constant temperature

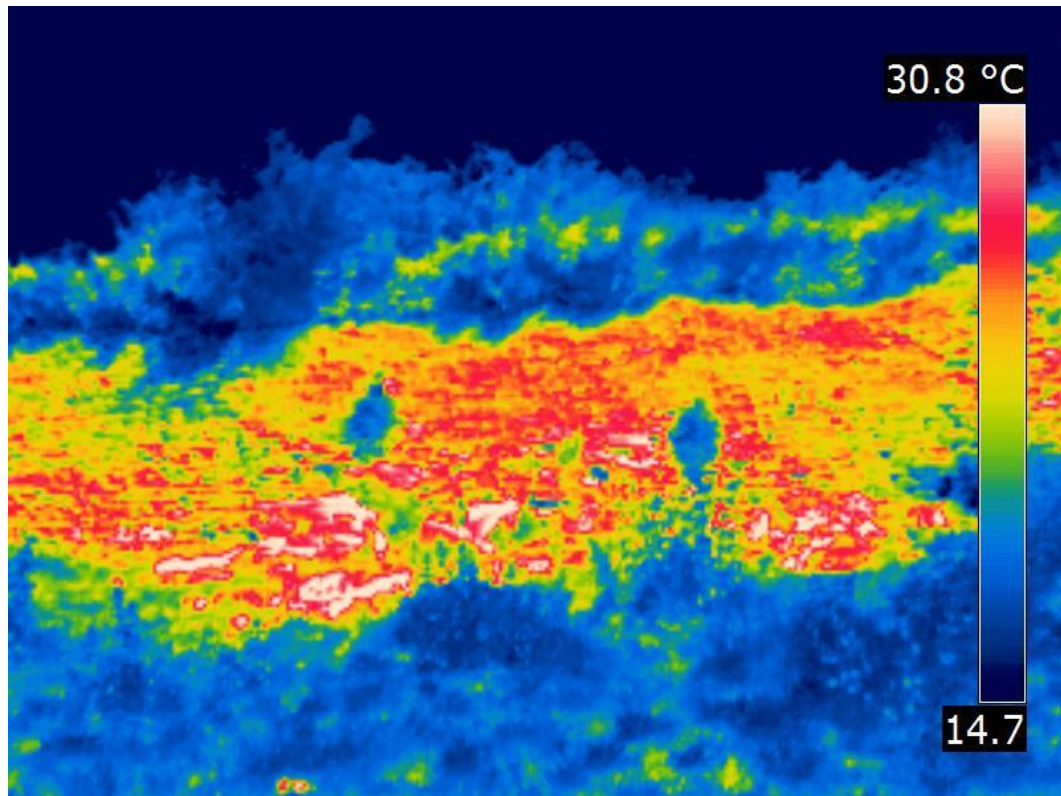


Image taken 10:30 07/06/13; cooler area between vegetation no longer visible. Some surface temperature variation seen, corresponding to variation in face construction and weathering of areas of stone.

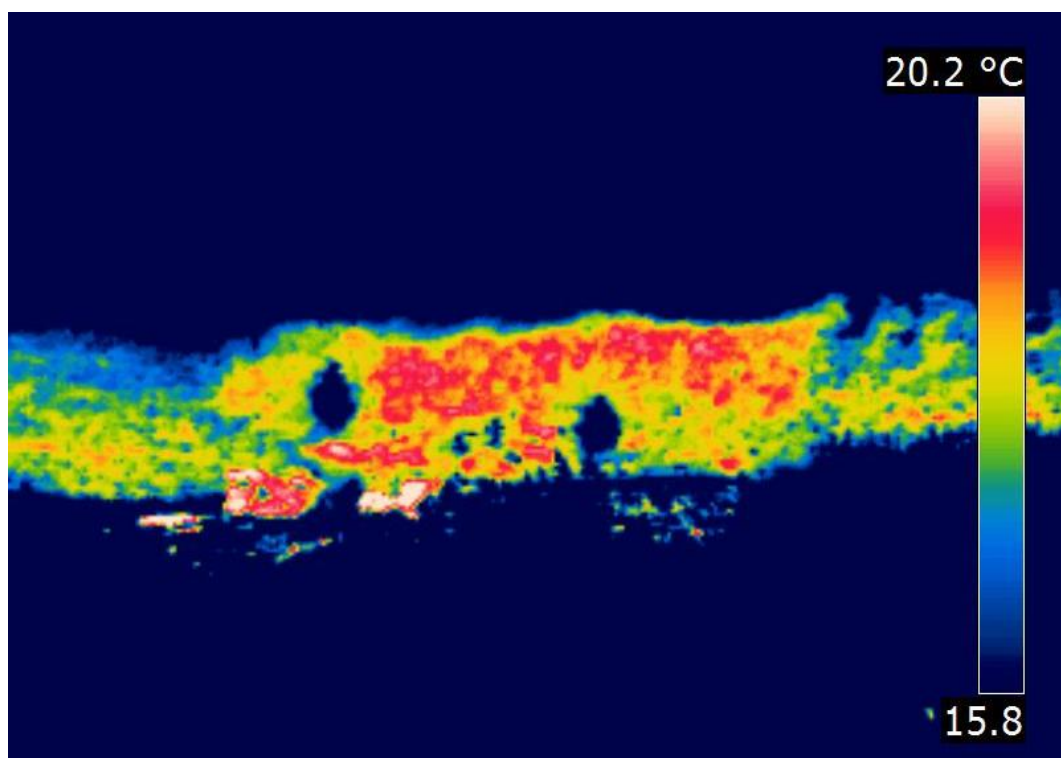


Image taken 13:00 07/06/13; Cooler area between vegetation becoming visible. Temperature differences between wall sections/constructions either side also visible.

A5.1.4 Section 4



Visual image: Section 4

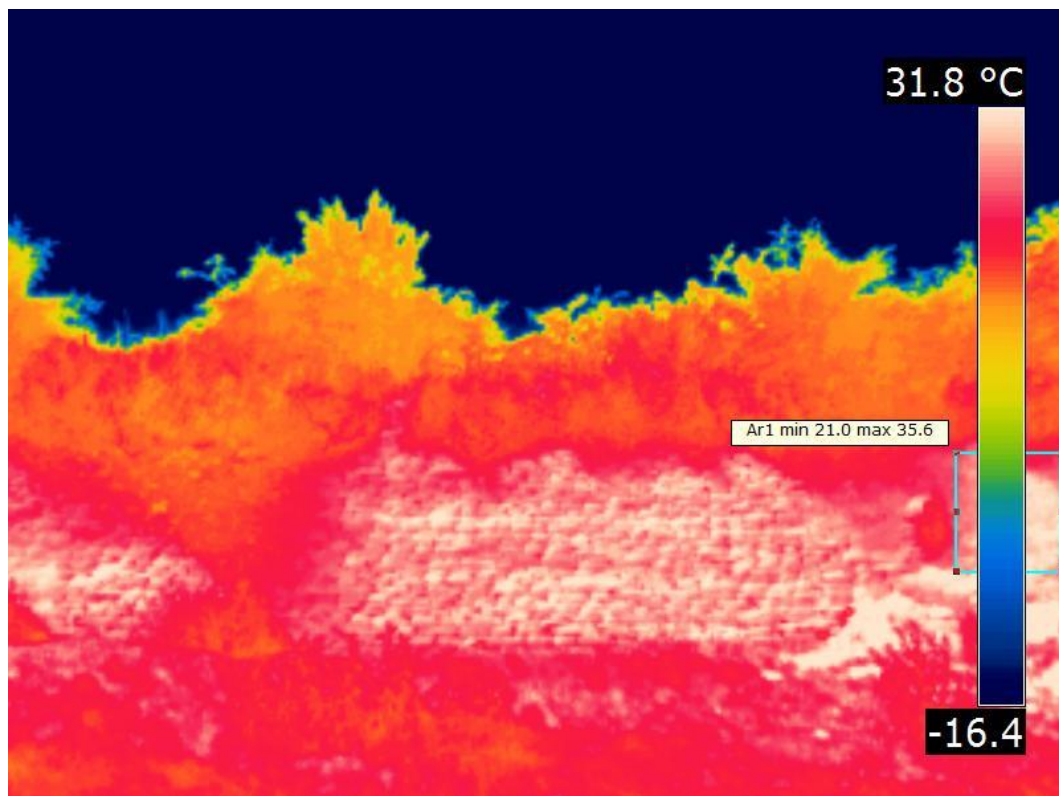


Image taken: 15:00 06/06/13; uniform temperature seen across wall. Cooler areas associated with shading at this time.

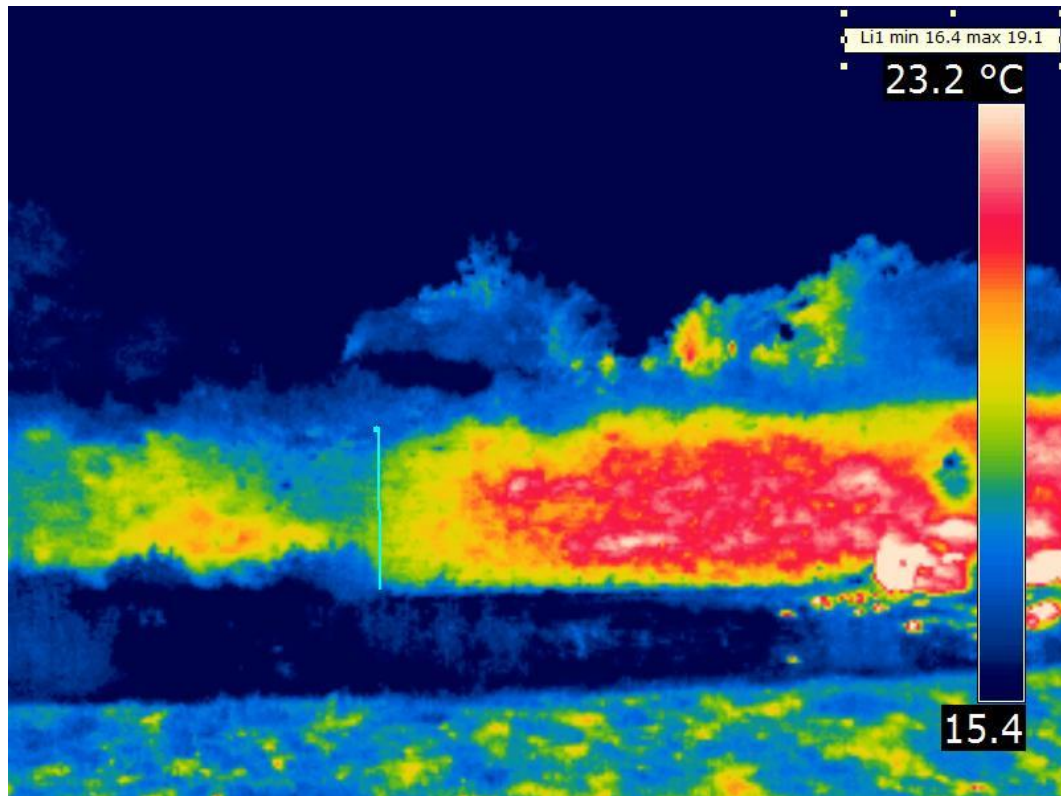


Image taken 17:30 06/06/13; uniform temperature across section. Distinct temperature difference between section 4 and section 5 can be seen (marked)

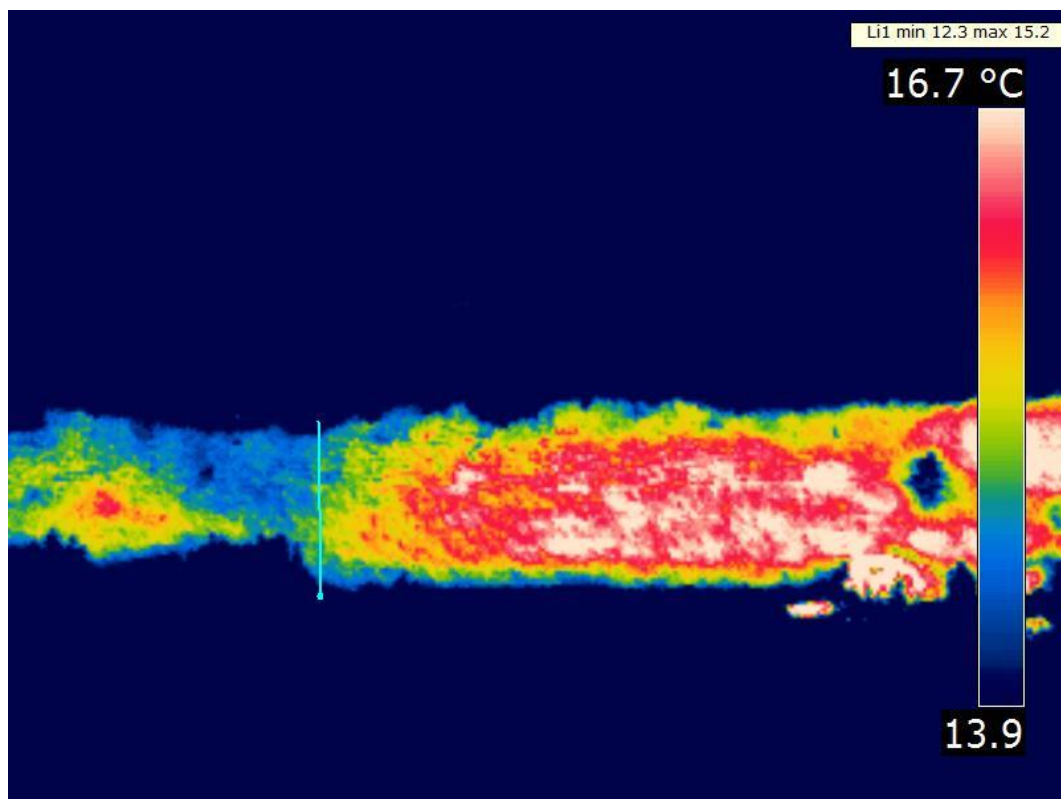


Image taken: 20:00 06/06/13; as at 17:30 distinct temperature difference to adjacent section can be seen.

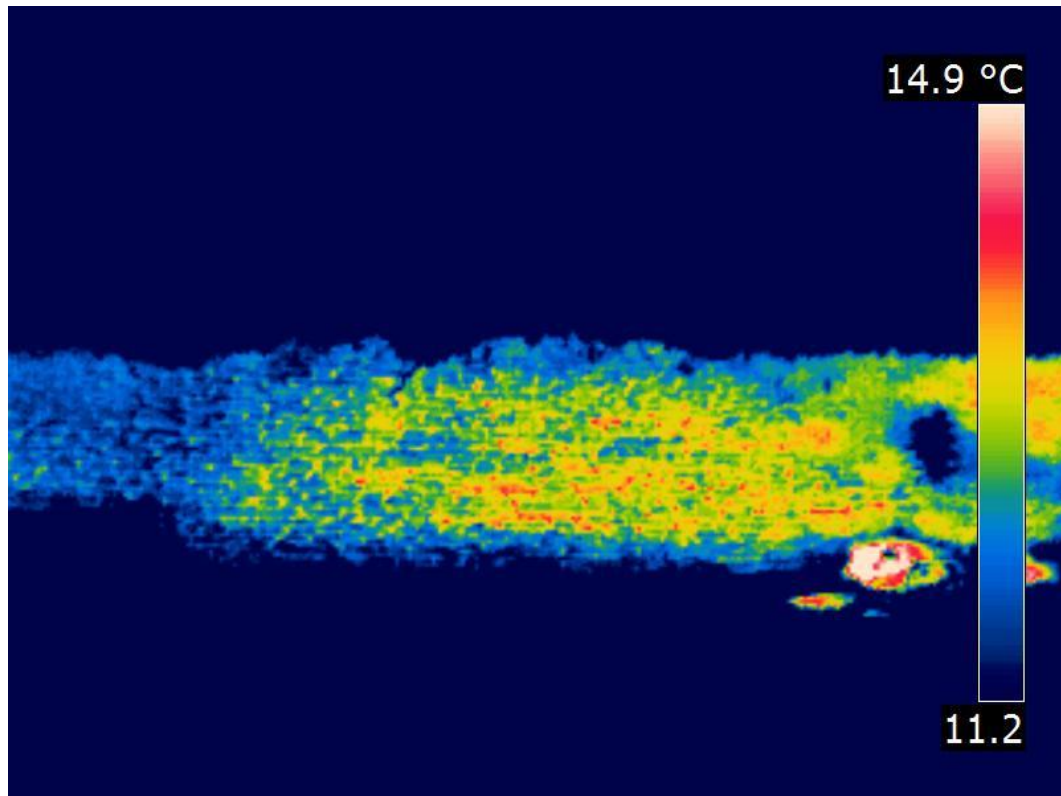


Image taken 22:00 06/06/13; temperature patterns as before. Two cooler areas in centre of wall can be seen, suggesting they may be in better contact with backfill than that around it.

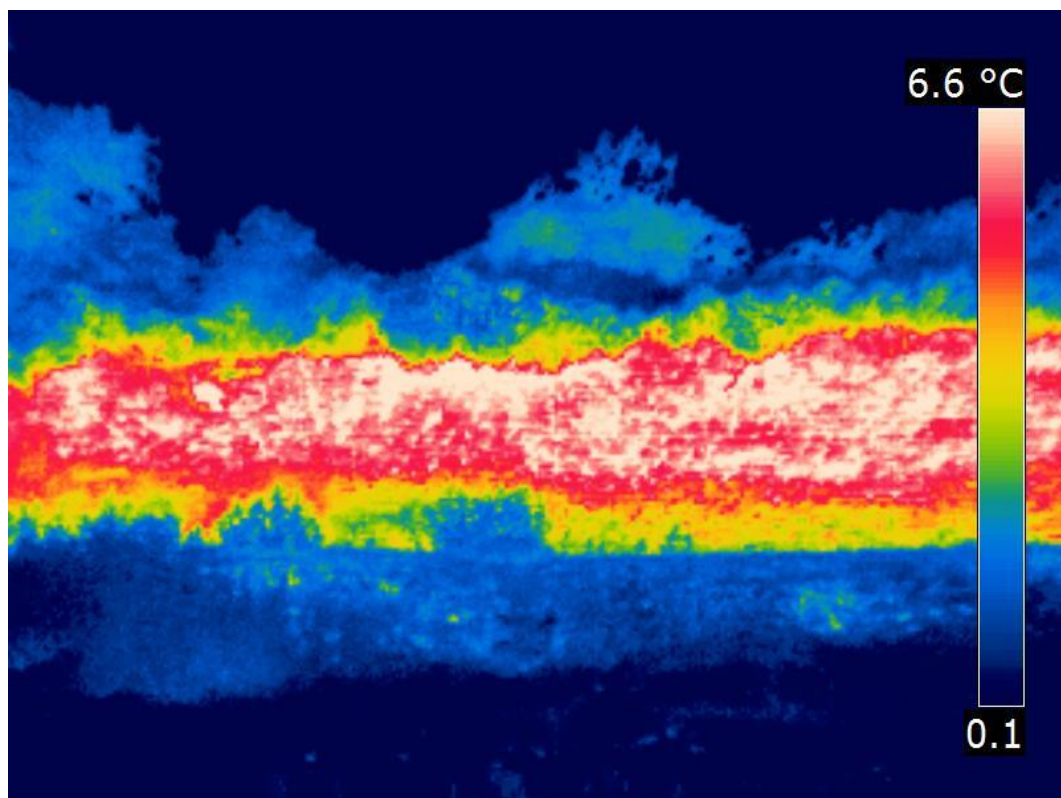


Image taken 05:30 07/06/13; uniform temperature across majority of wall seen.

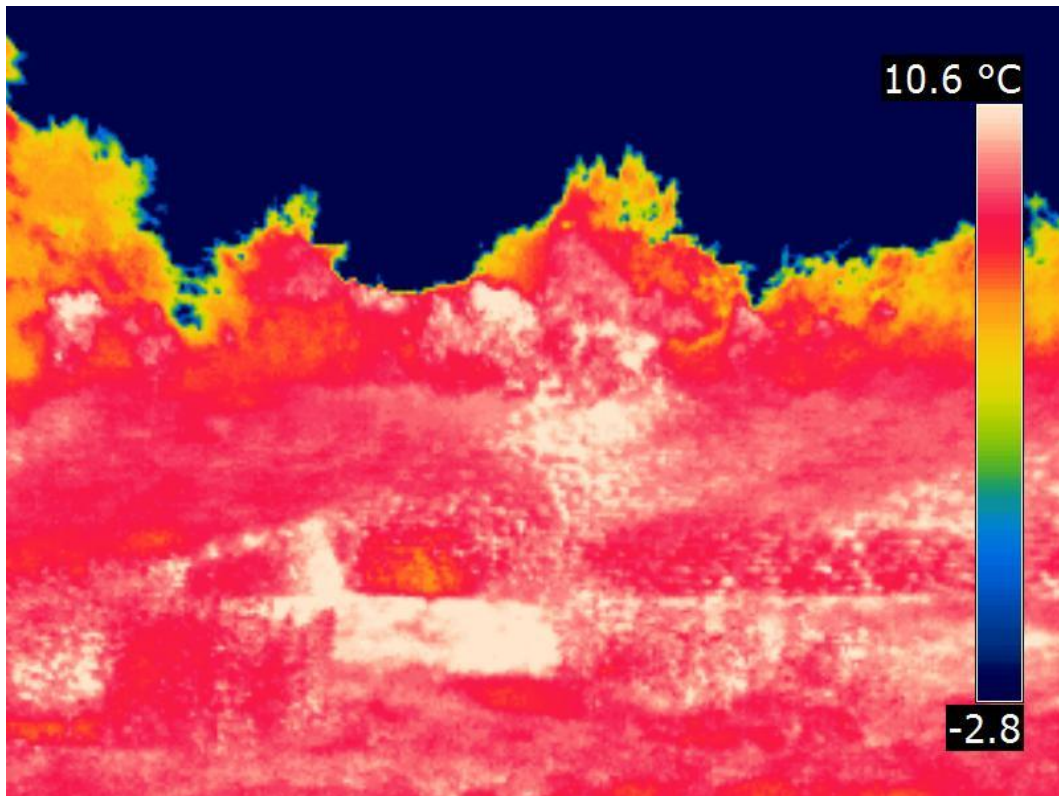


Image taken 08:00 07/06/13; uniform temperature seen across wall, variations associated with shading at this time.

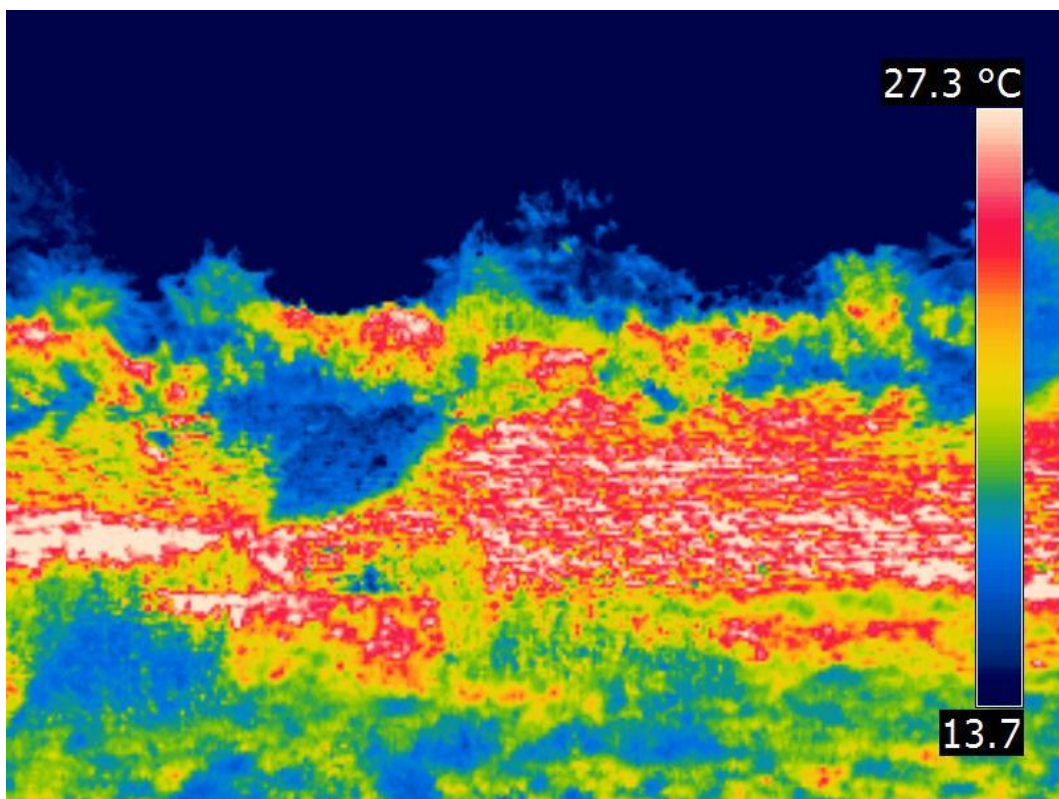


Image taken 10:30 07/06/13; temperature variations seen across wall surface. Significantly cooler area associated with shading.

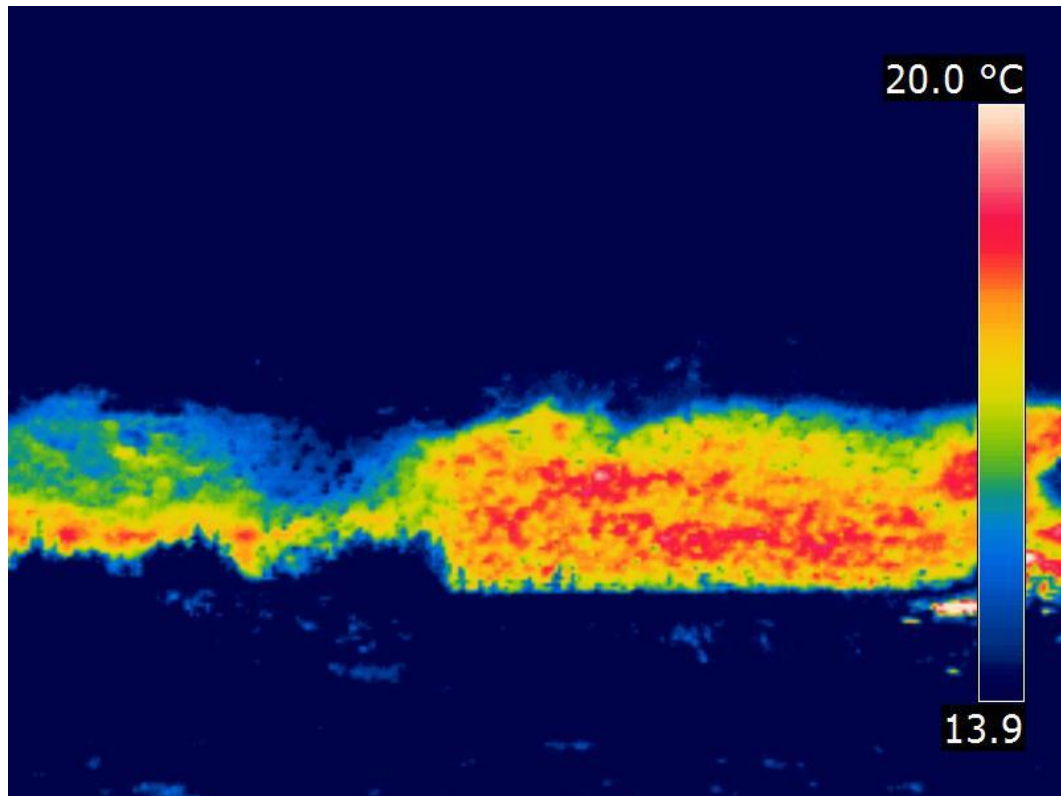


Image taken 13:00 07/06/13; uniform temperature across wall section. Cooler section to top of wall associated with overhanging vegetation.

A5.1.5 Sections 5&6



Visual image: significant proportion of this area mortared and shaded by large tree

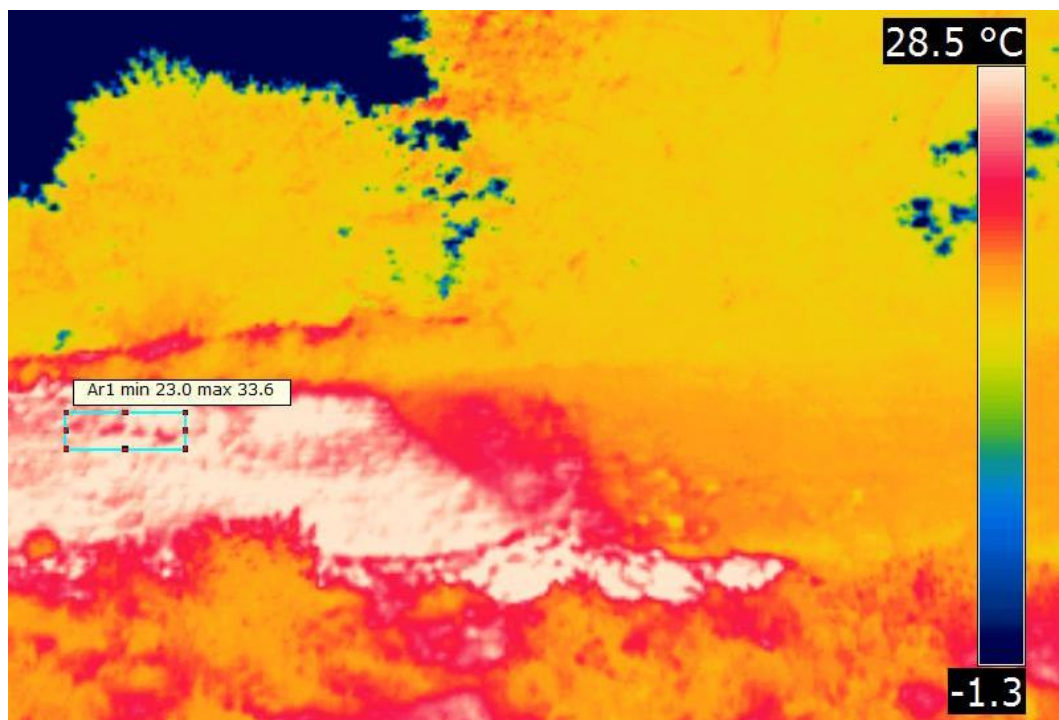


Image taken: 15:00 06/06/13; little information shown from thermal image, main temperature variation between mortared and non-mortared area. Mortared area also shaded by tree. Some variation shown where masonry missing/weathered (highlighted)

Image taken: 17:30 06/06/13; image in main body of thesis.

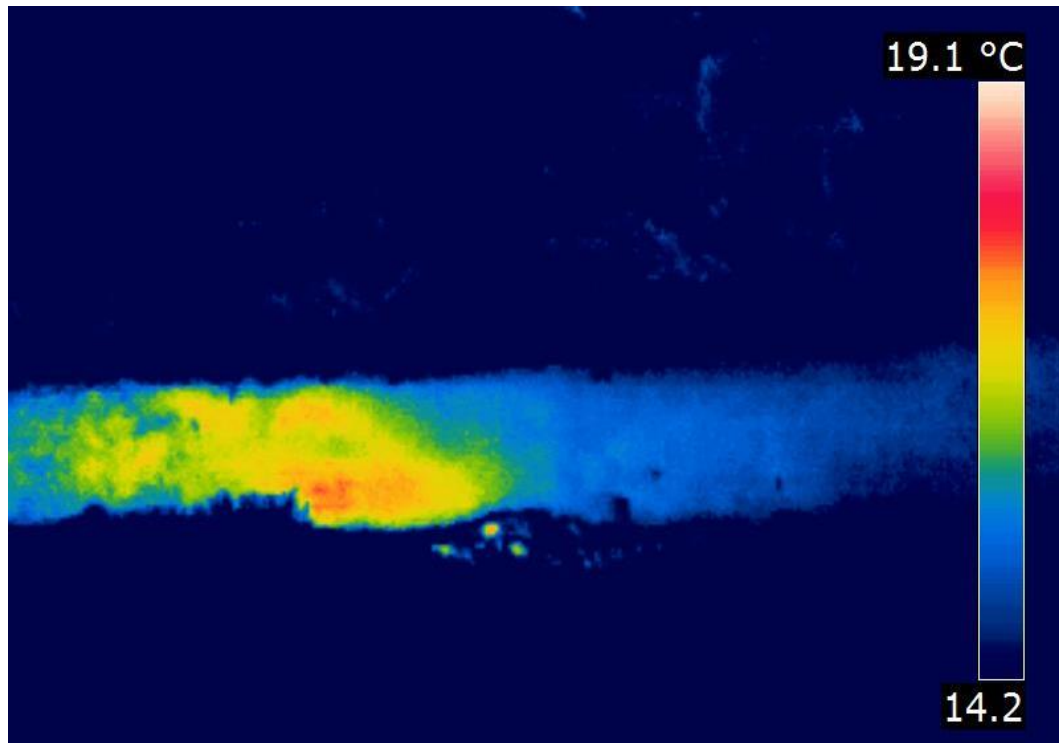


Image taken: 20:00 06/06/13; no information shown. Main temperature change between mortared and non-mortared area.

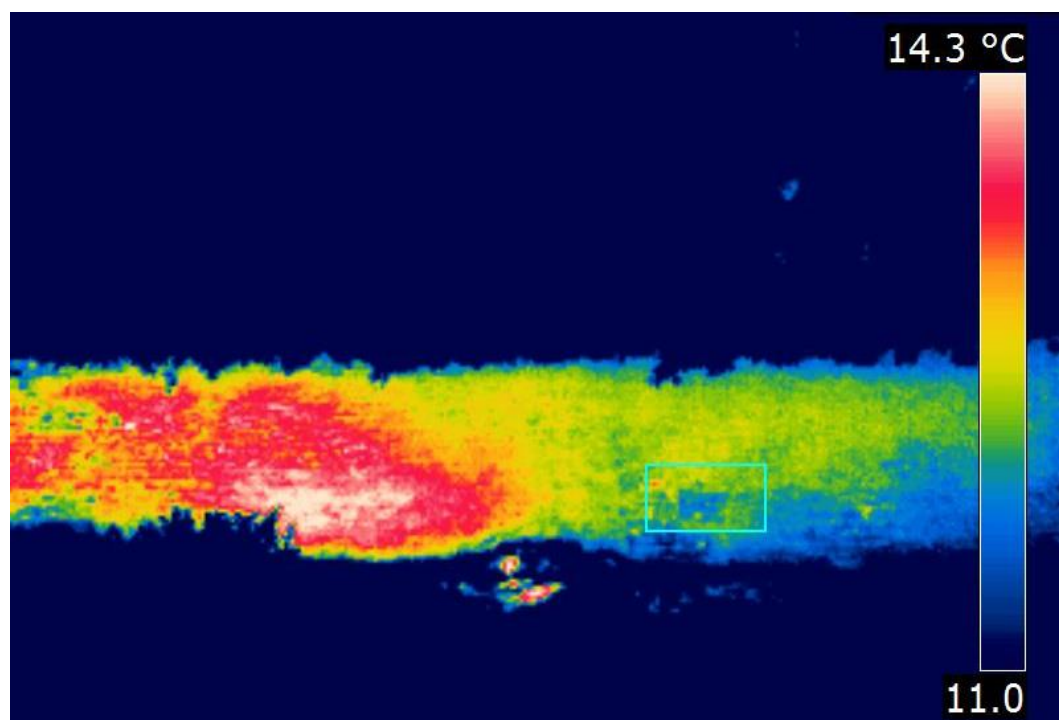


Image taken: 22:00 06/06/13; main temperature difference between mortared and non-mortared area as above. Cooler area (highlighted) looks to correspond to an area of weathered stone.

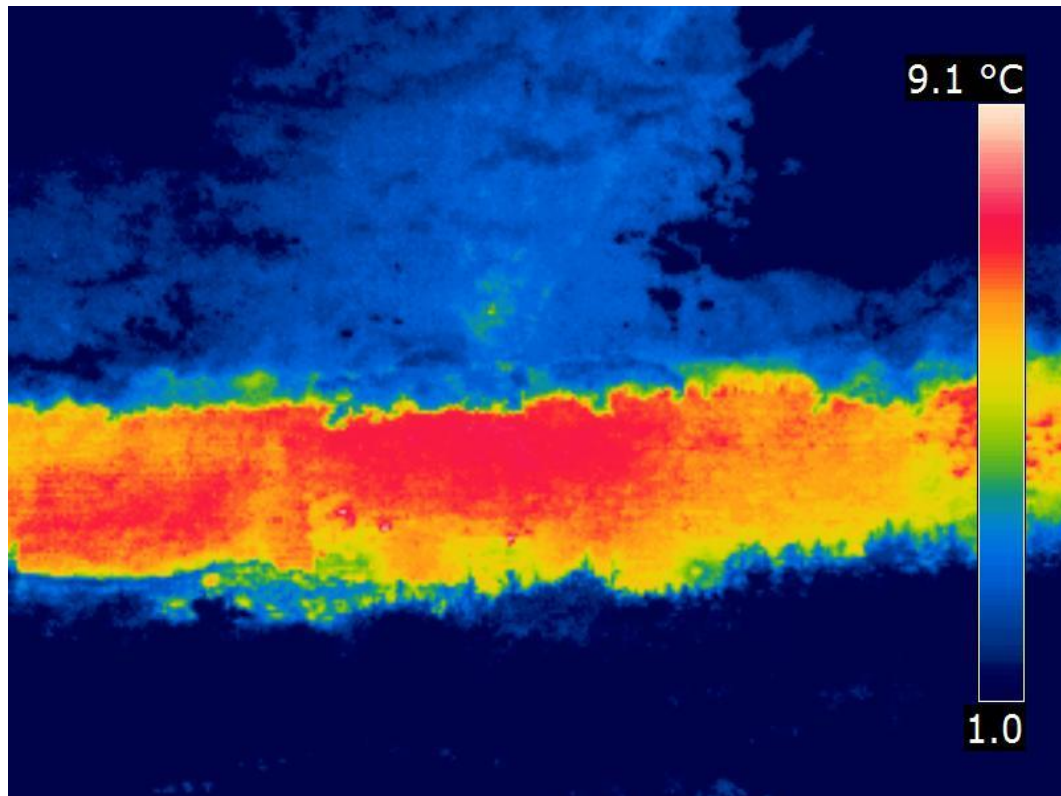


Image taken: 05:30 07/06/13; no distinguishable features shown

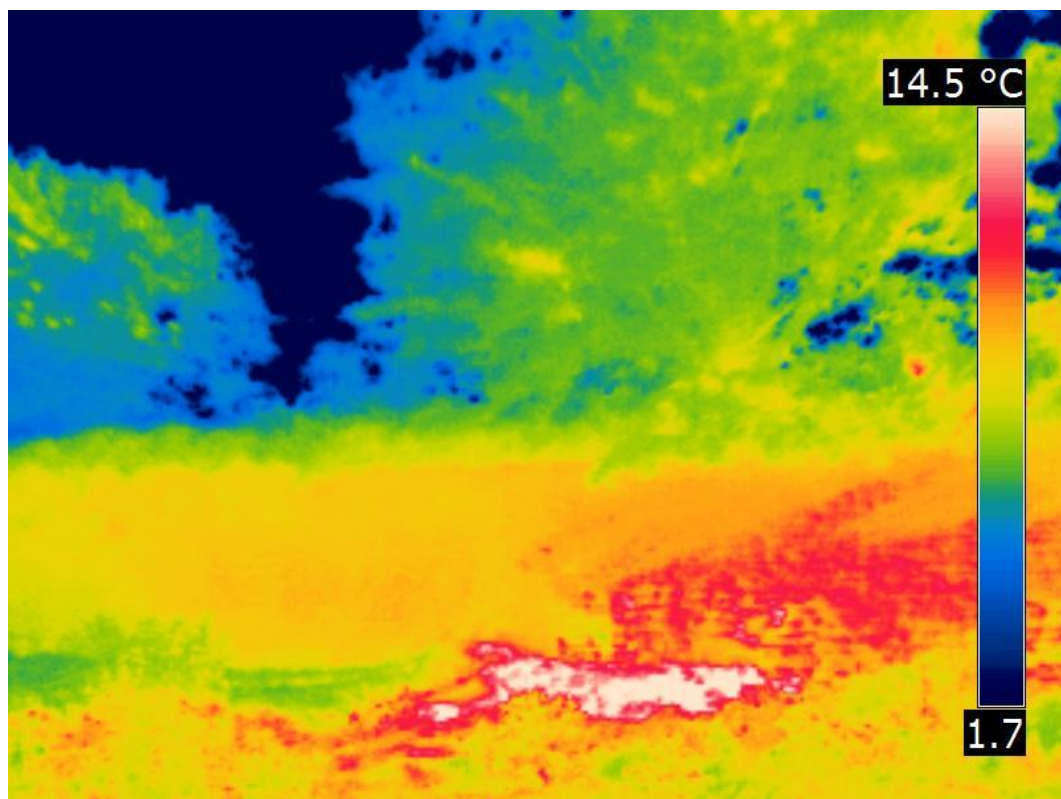


Image taken: 08:00 07/06/13; main temperature variations seen between shaded and non-shaded areas

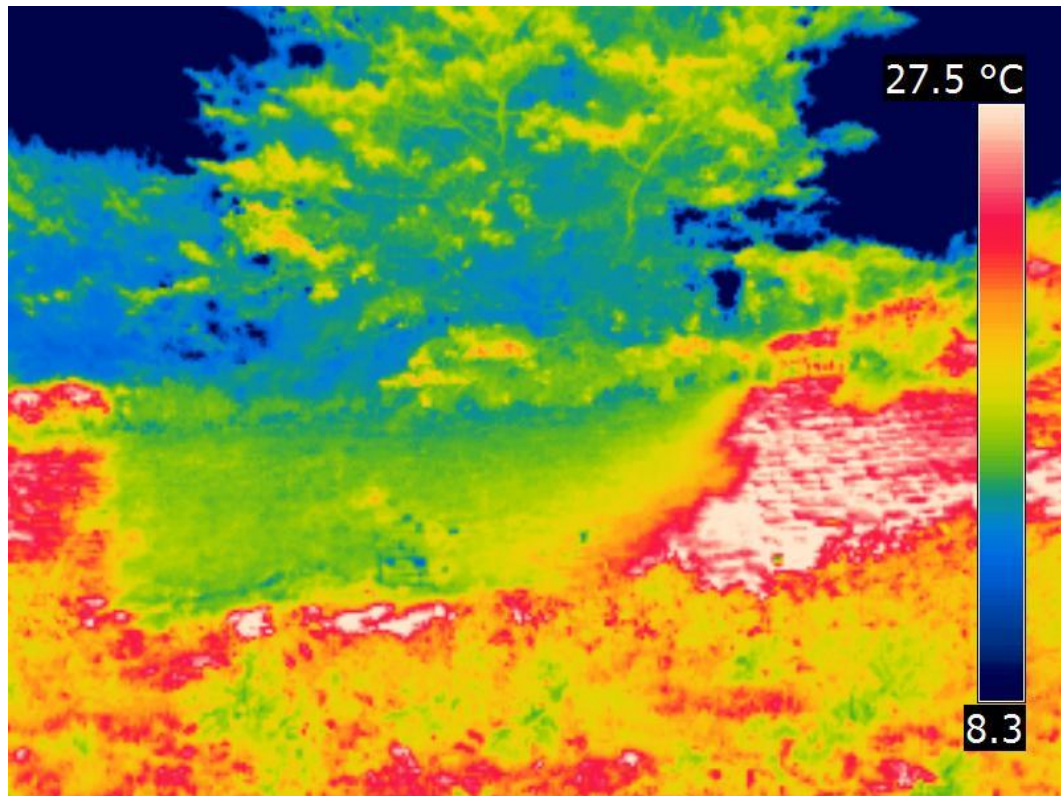


Image taken: 10:30 07/06/13; as for 08:00. Cooler points in shaded area associated with missing stone as face

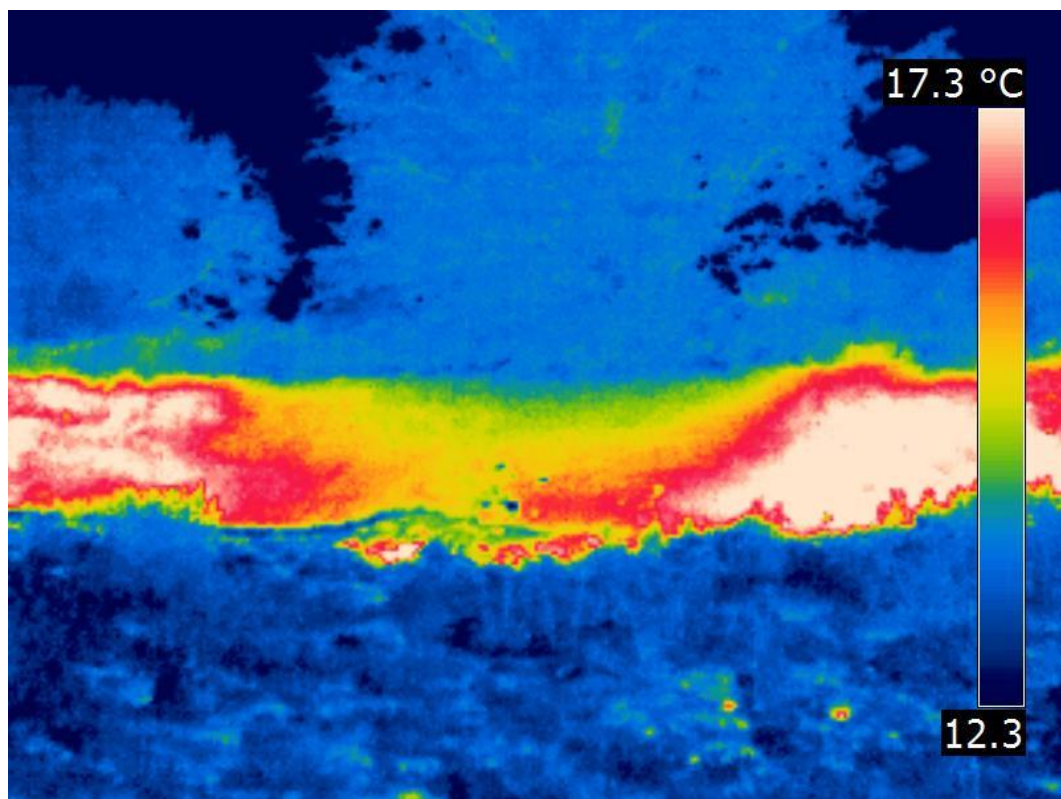
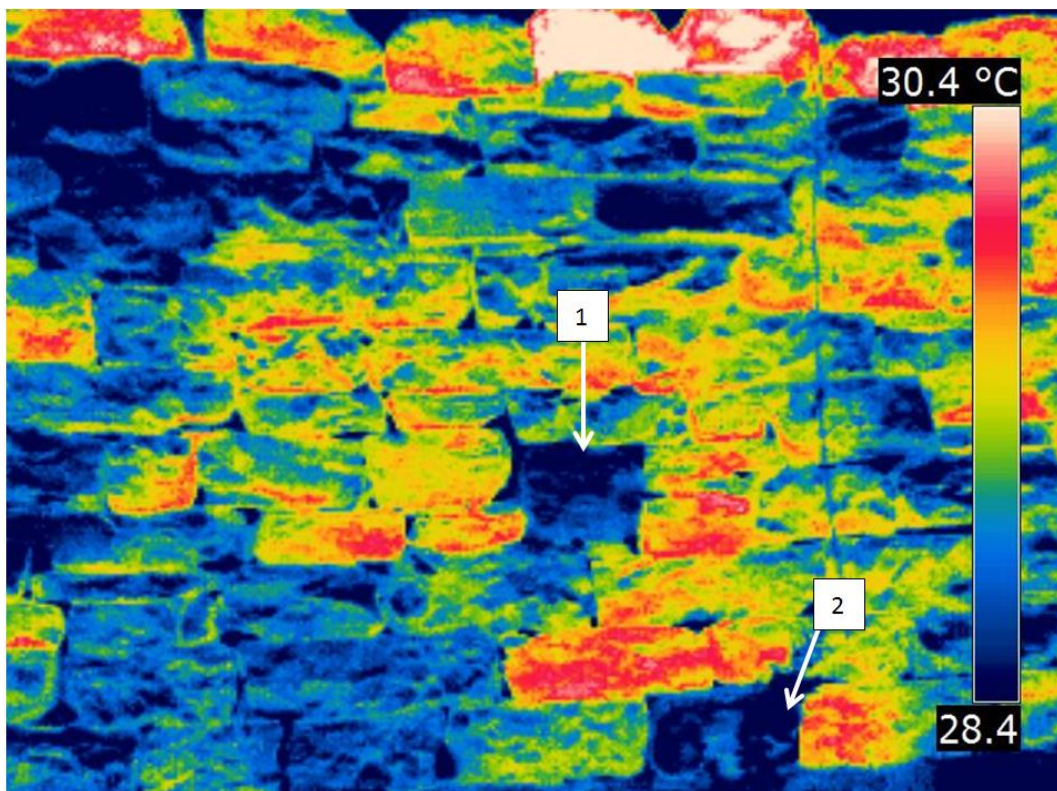
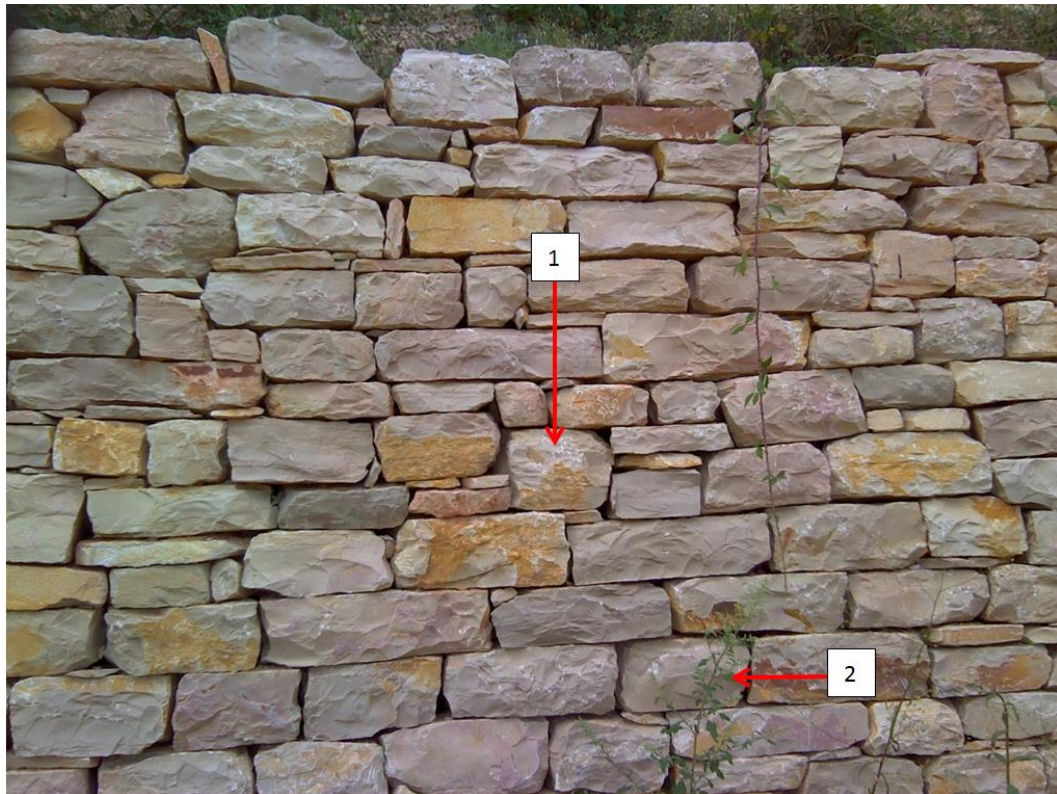
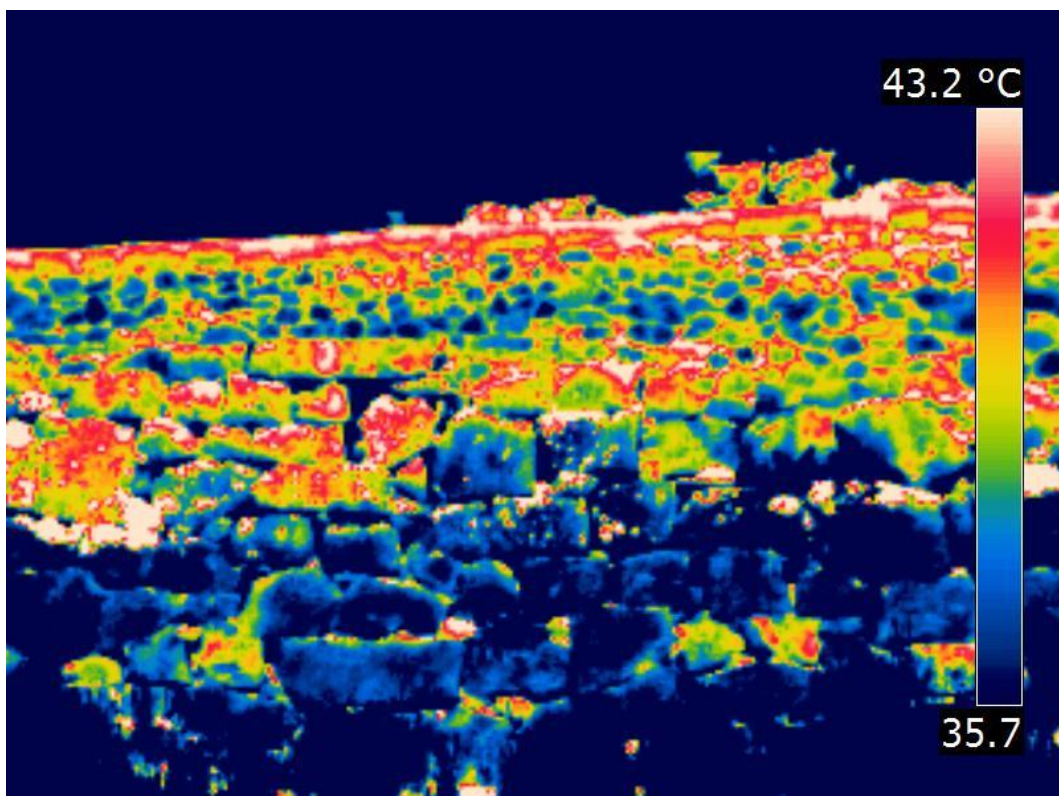


Image taken 13:00 07/06/13; as for 10:30

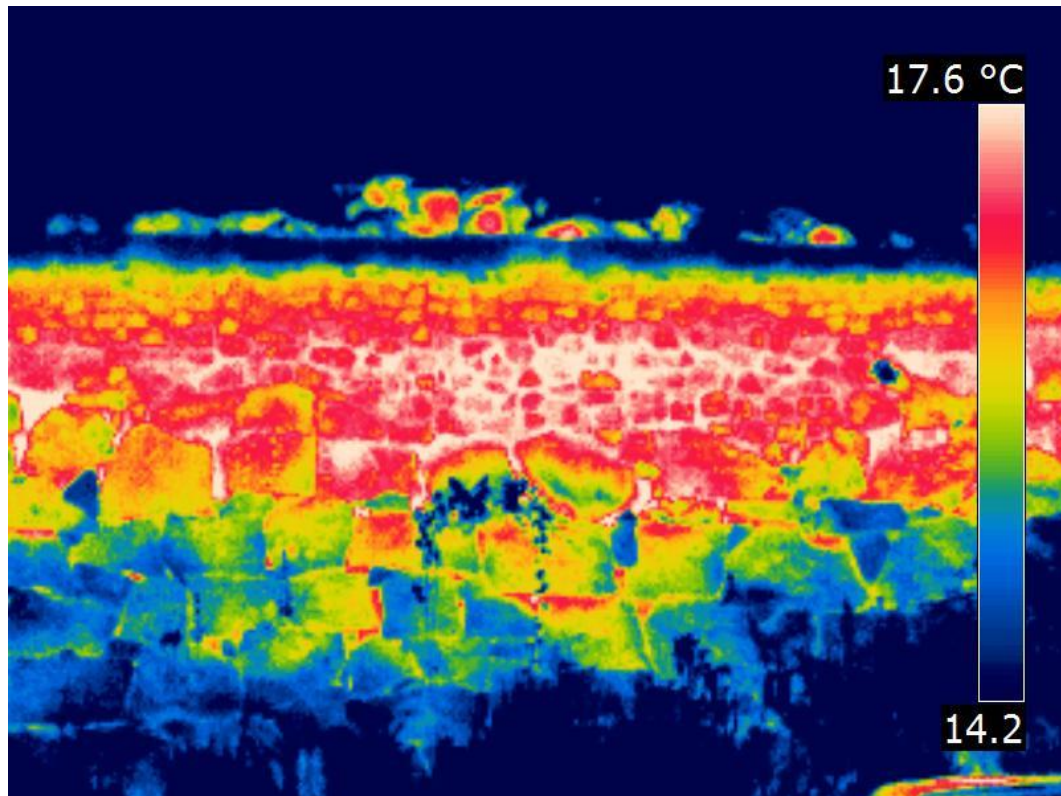
A5.2 Additional Thermal Images of French Construction



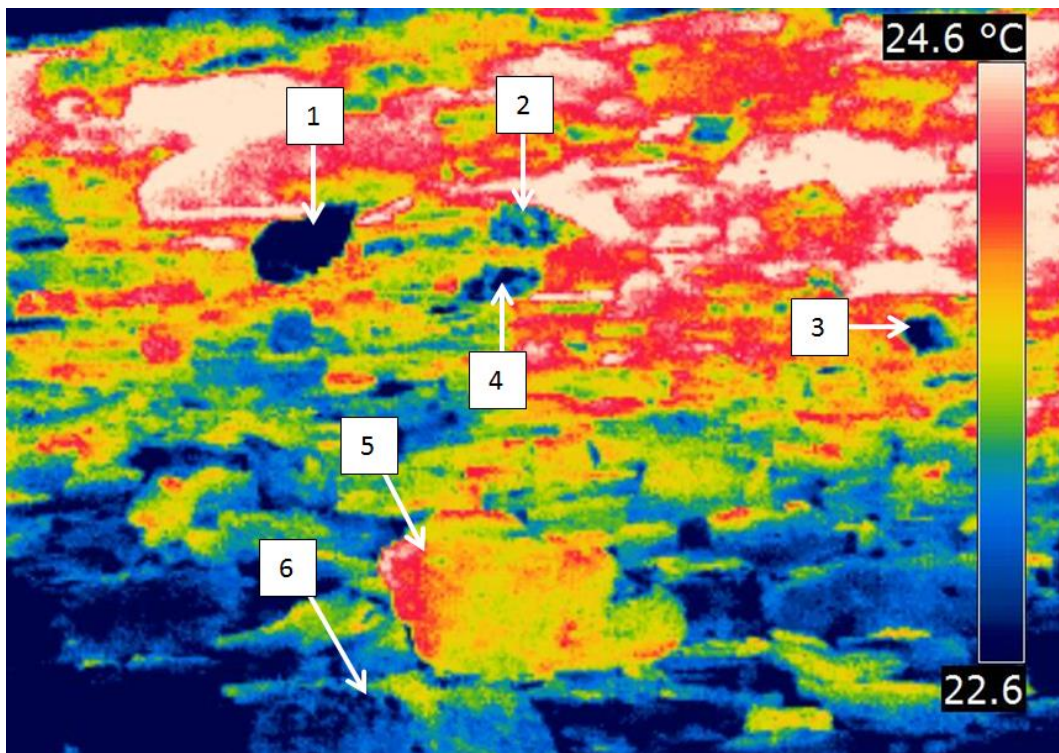
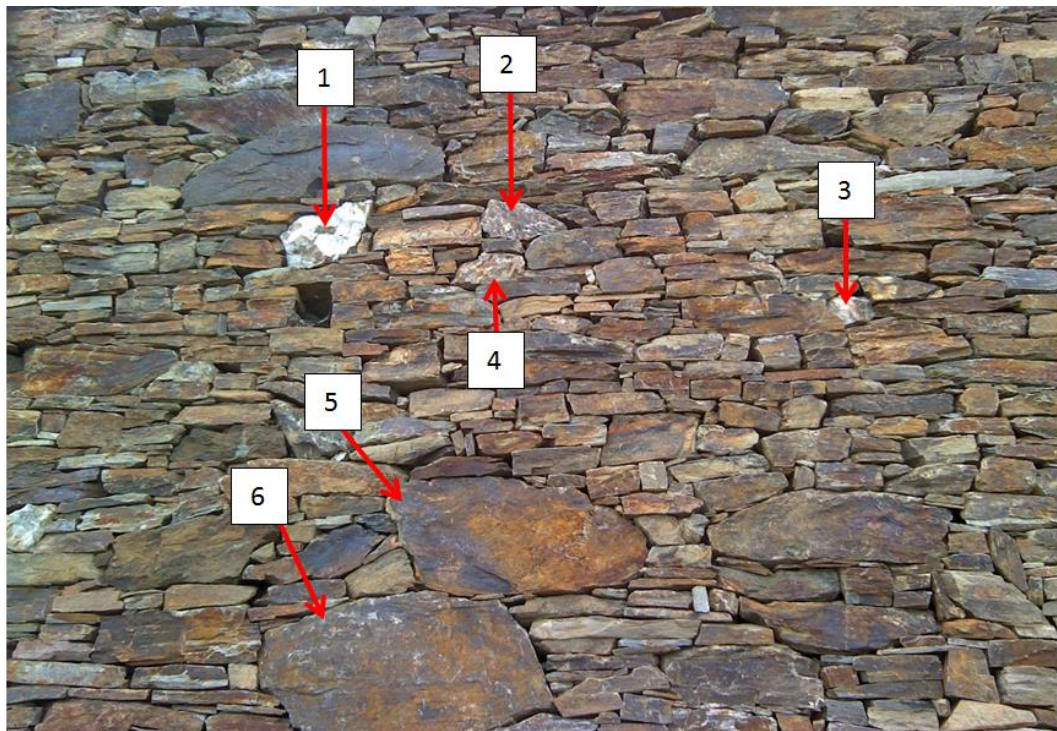
East facing Wall at the Monastery, St Enimie, France Approximately 1.25m high. Taken 14:10 06/09/13. Stones 1 and 2 can be seen to be cooler than those around then suggesting better contact to the backfill.



South Facing Historic Wall, Pont du Monvert, supporting the D998, France. Taken 15:30 06/09/13. When this image was taken the wall was in full sun and shows the temperature fluctuation across the surface of the stone as seen in Figure 7.19 (Ffestiniog Railway). When imaged in the morning (below), more uniform temperatures across the stone surfaces were seen.

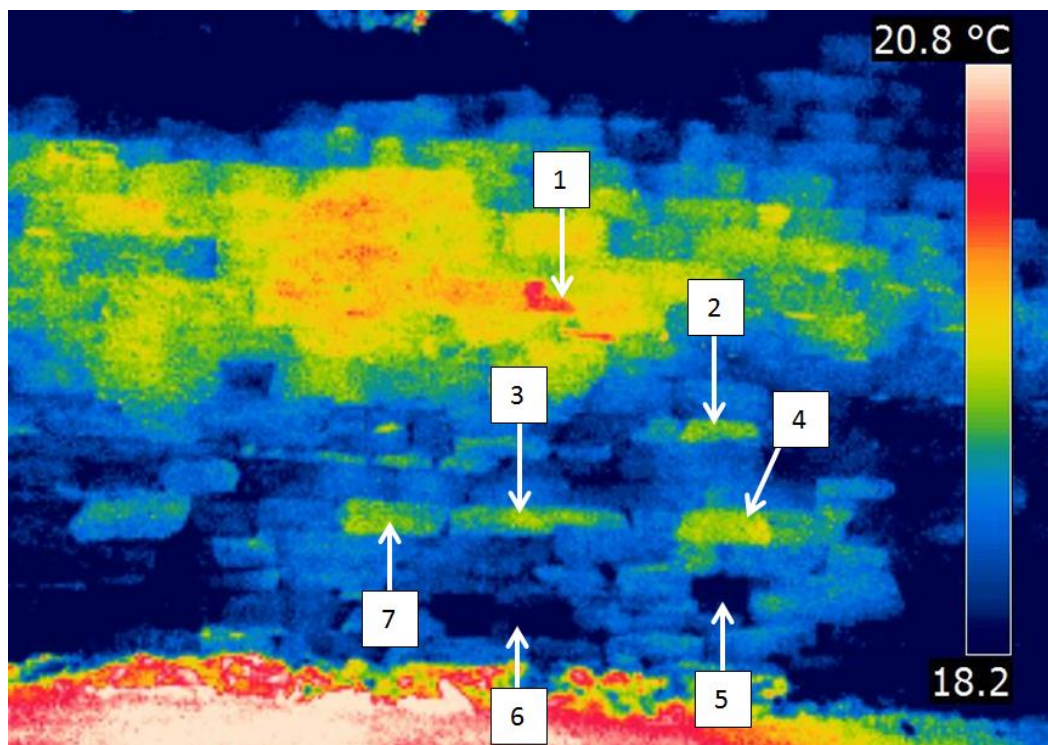
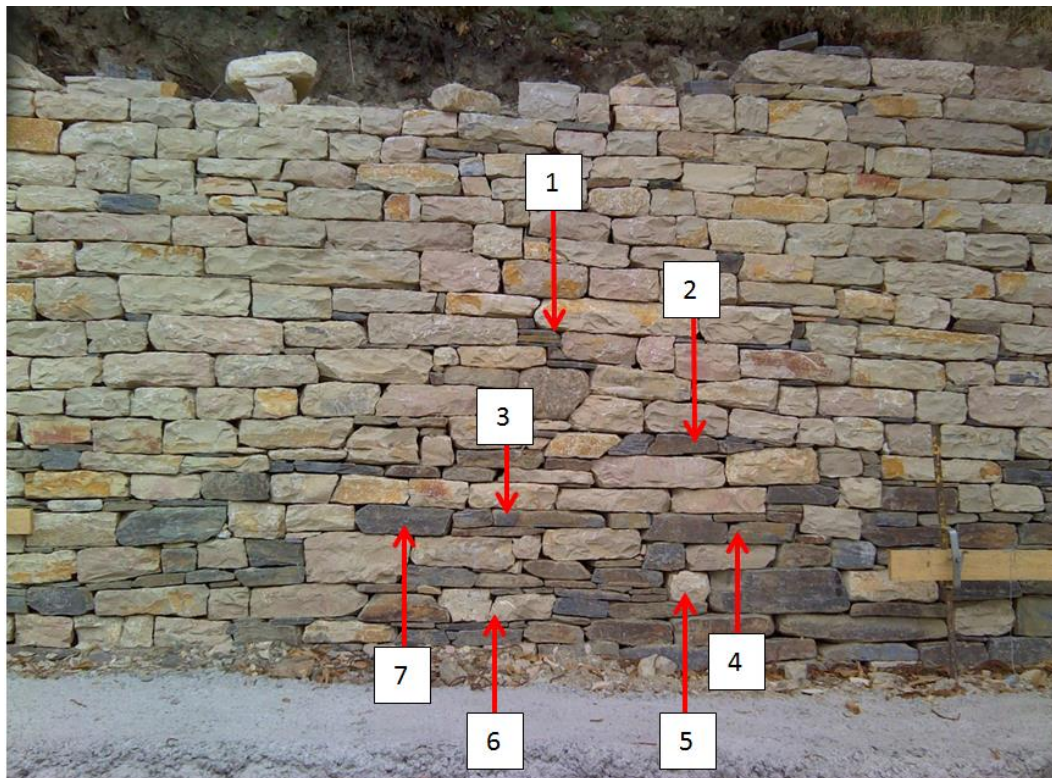


Historic Wall, Pont du Monvert. Taken 08:00 07/09/13. More uniform temperatures across individual stone faces seen at this time. The top section of the wall is a mortared parapet to the road and can easily be identified in the image.



3m High Wall North facing wall in L'Espinass, France adjacent to that shown in Figure 7.14. Taken 10:45 07/09/13. Stones 1-4 show the effects of differing stone colour.

Being noticeably lighter and cooler than those around them. Stones 5&6 while appearing to be of similar size at the wall face stone 6 is cooler suggesting it potentially penetrates further into the wall and hence has better contact to the backfill. In this particular location it may also be an indication of differing material behind the wall as for the adjacent section.



South Facing Wall in L'Espinas on the D35. Constructed using a variety of stone around a construction area. Construction was not completed at time of imaging and had not been fully backfilled. Highlighted stones show the effects of differing stone colours locally. Generally a warmer area of construction can be seen to the top of the wall, this is likely to correspond to an area where backfill has not yet been placed fully. And corresponds to the area of wall not yet completed that can be seen in the visual image.

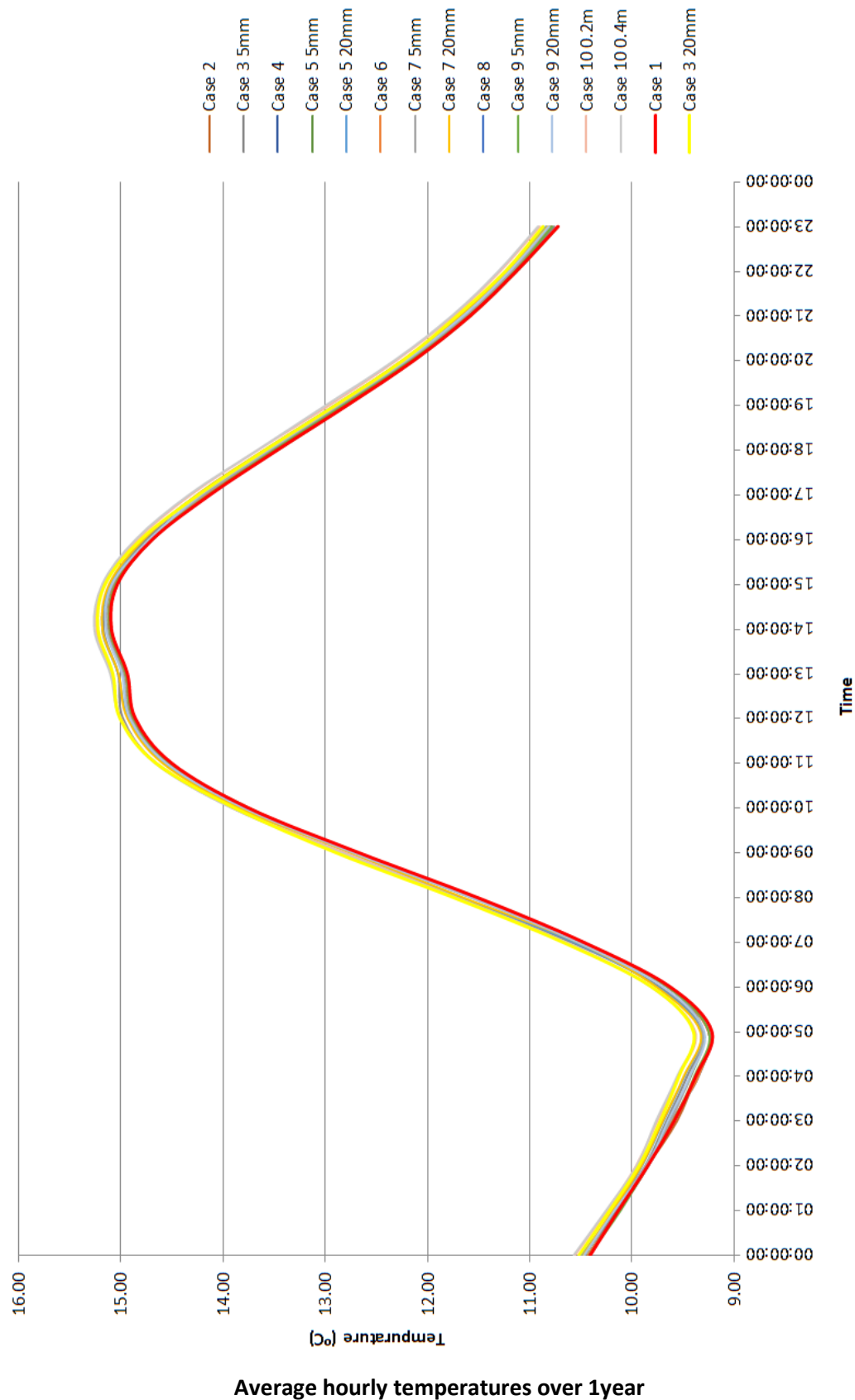
A5.3 Additional WUFI Data

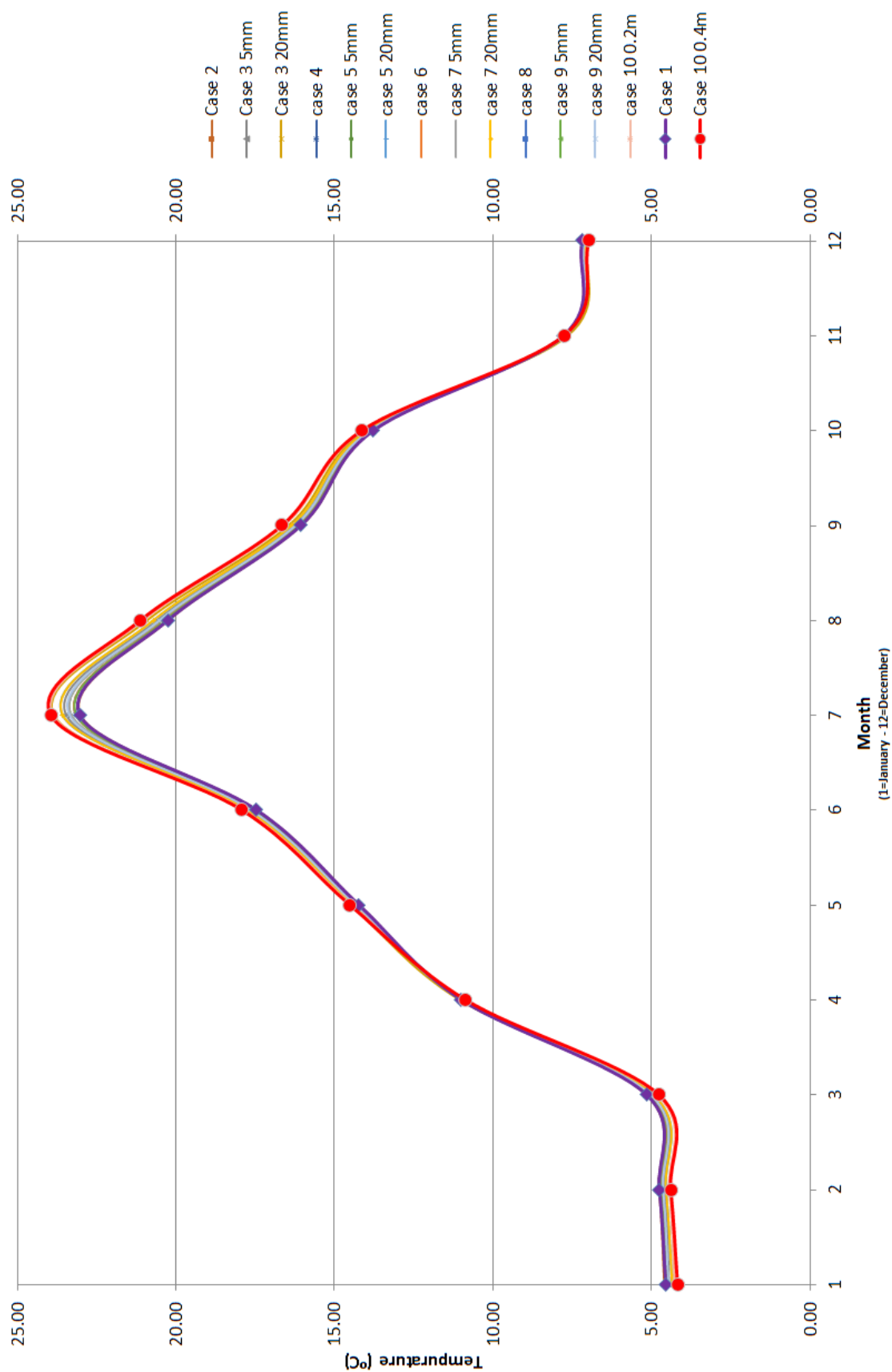
A5.3.1 East facing simulations

A5.3.2 West facing simulations

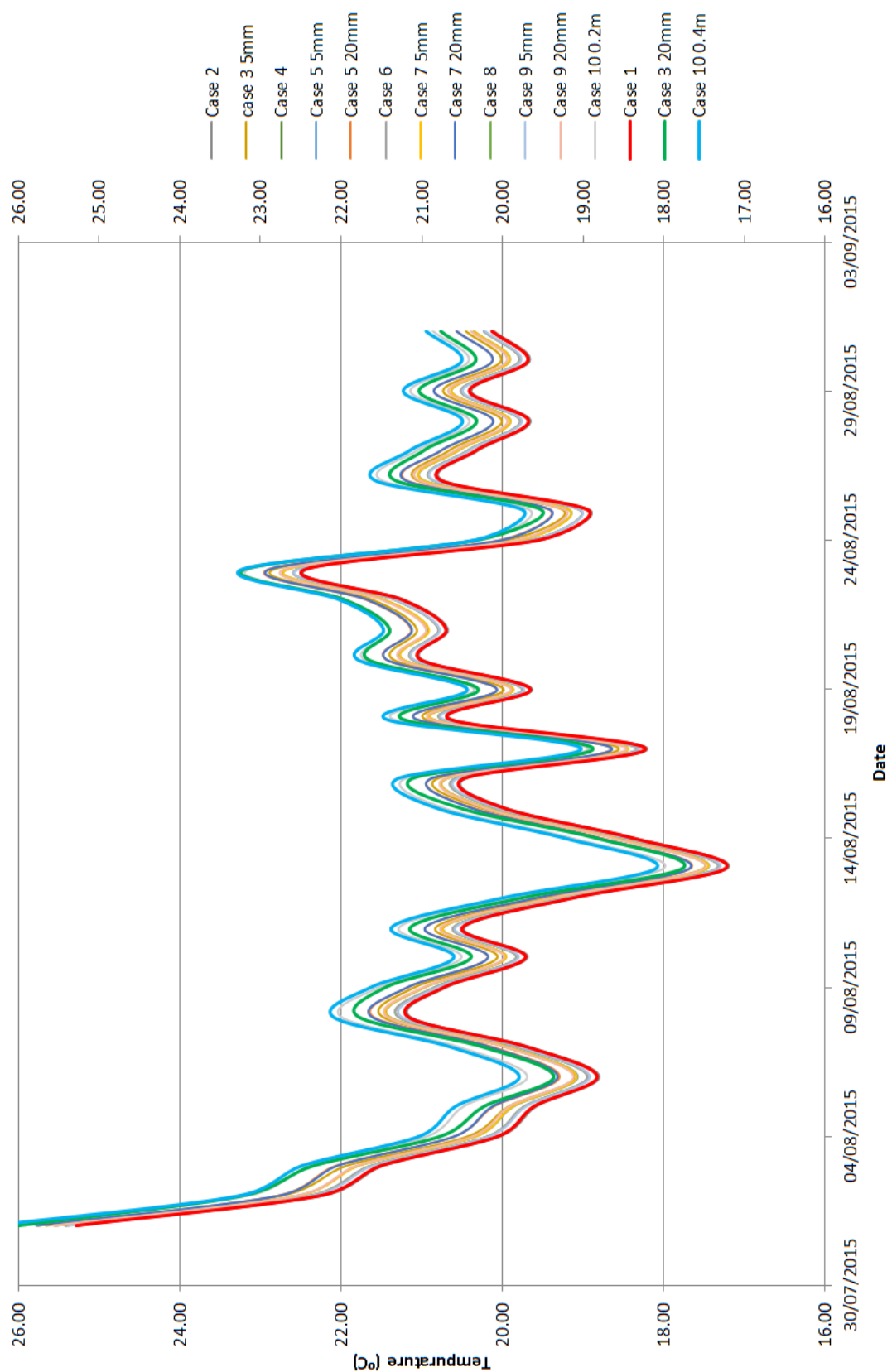
A5.3.3 North facing simulations

A5.3.1 East facing simulations

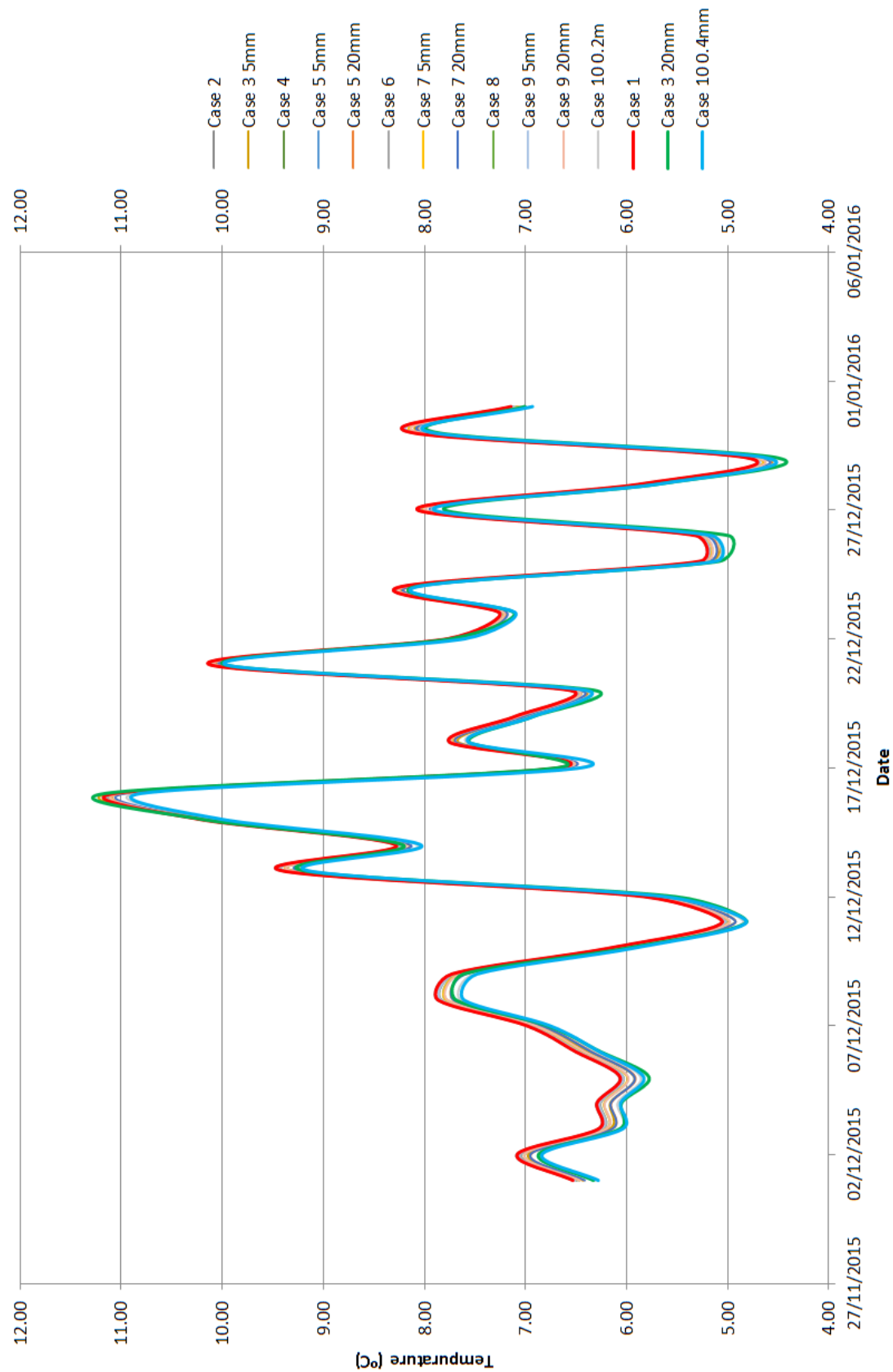




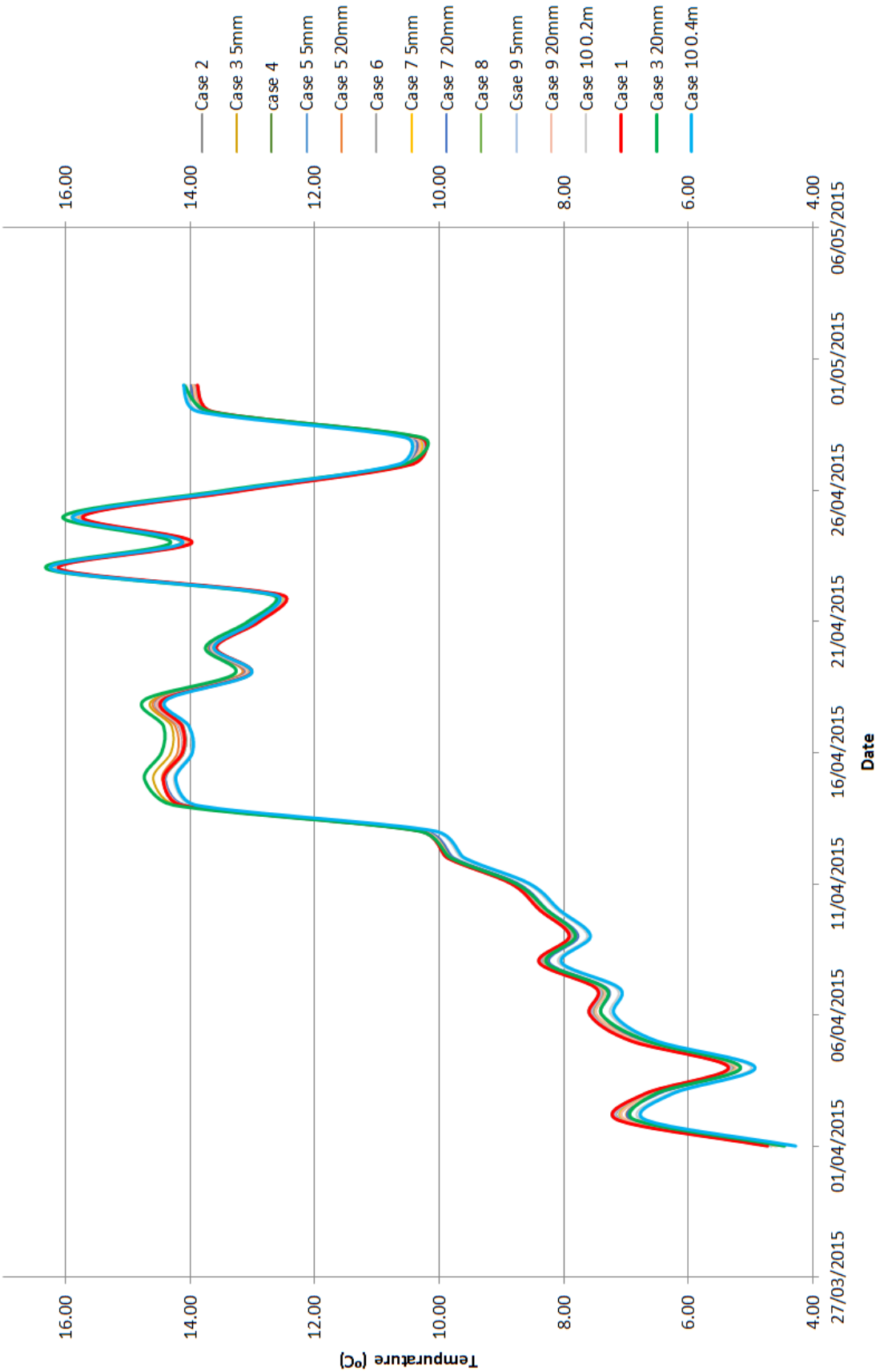
Style Temperature Comparison over 1 year



Temperature Plot for August with Case1, Case 3 20mm, and Case 10 0.4m highlighted

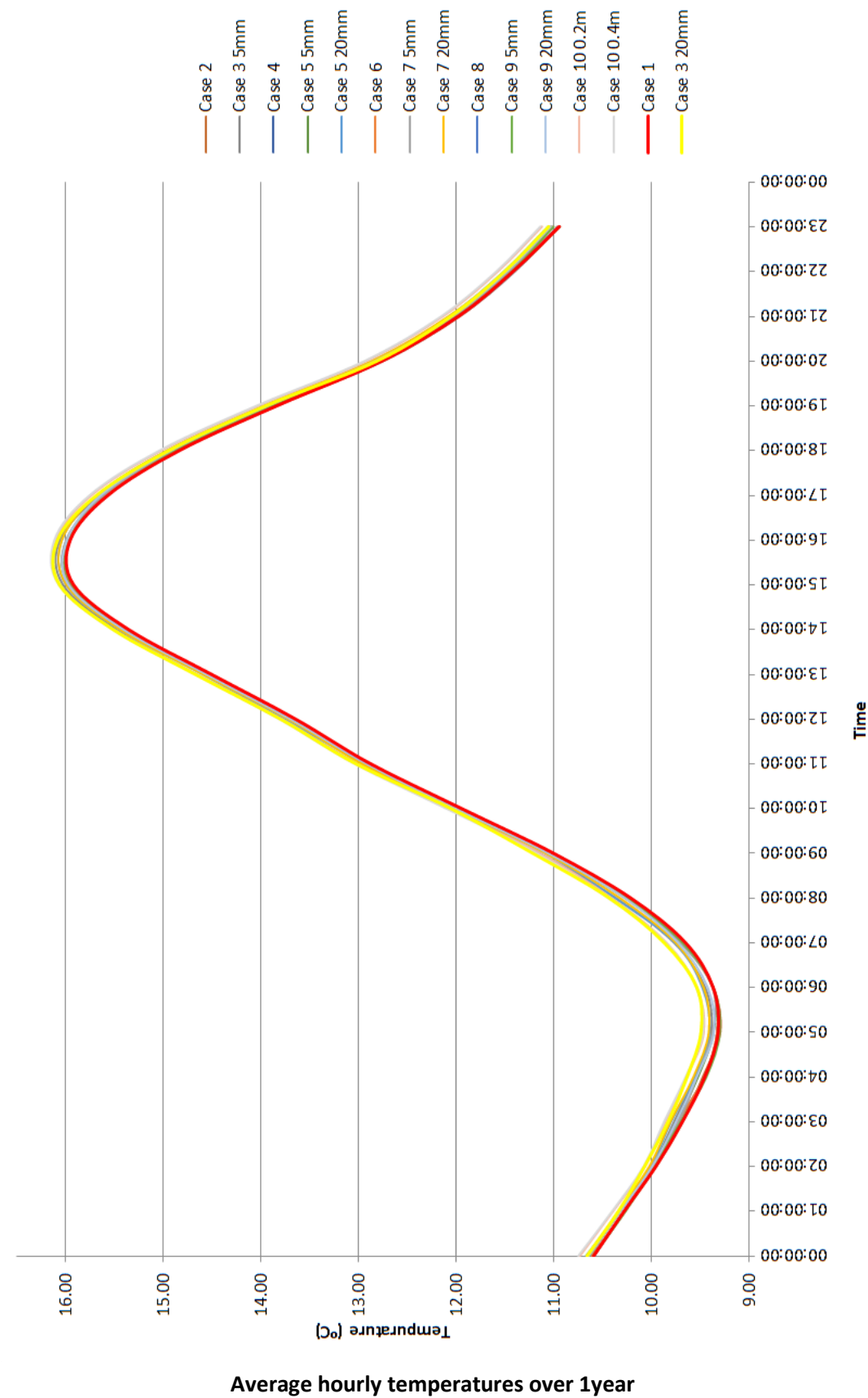


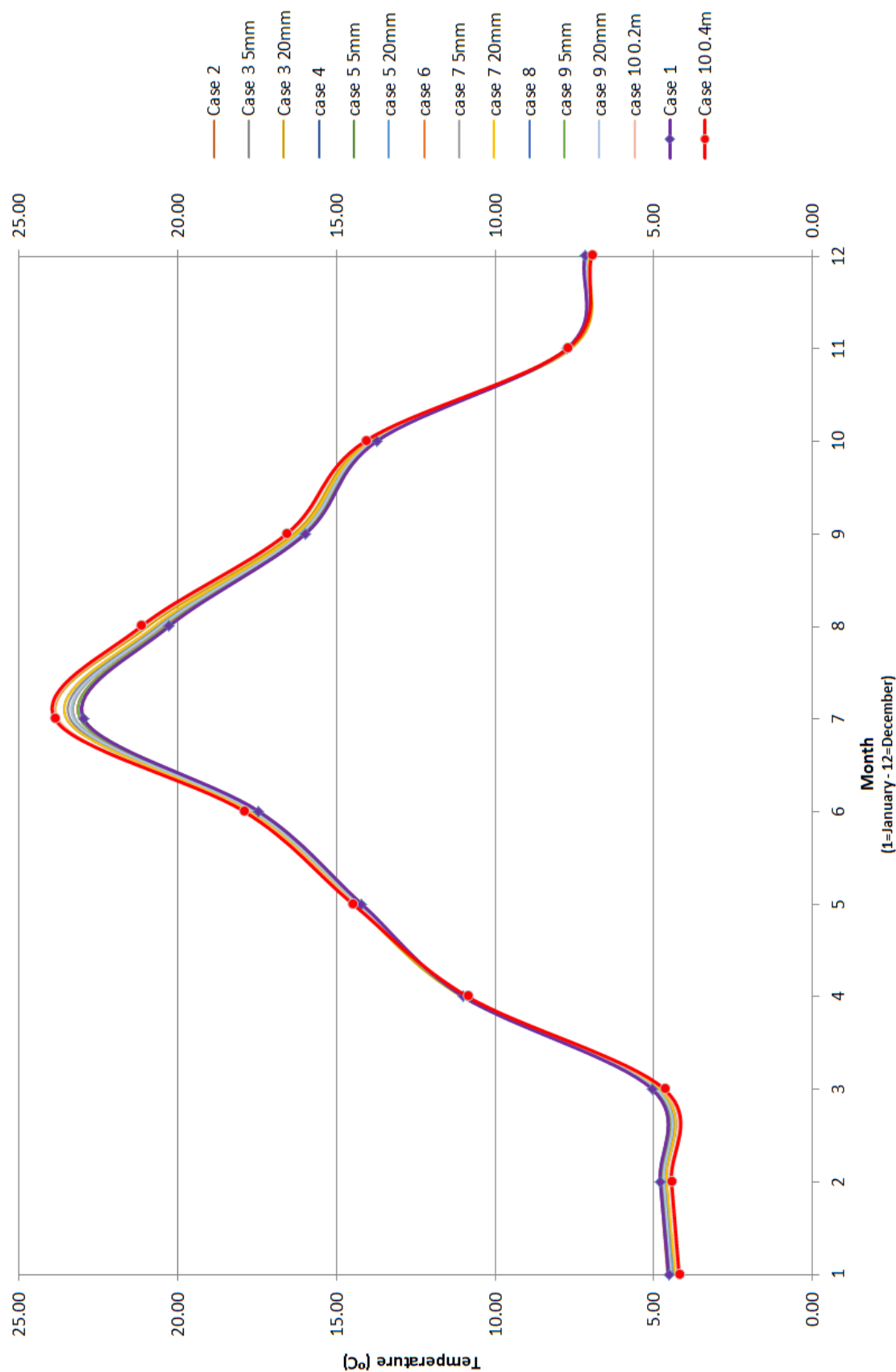
Temperature Plot for December with Case1, Case 3 20mm, and Case 10 0.4m highlighted



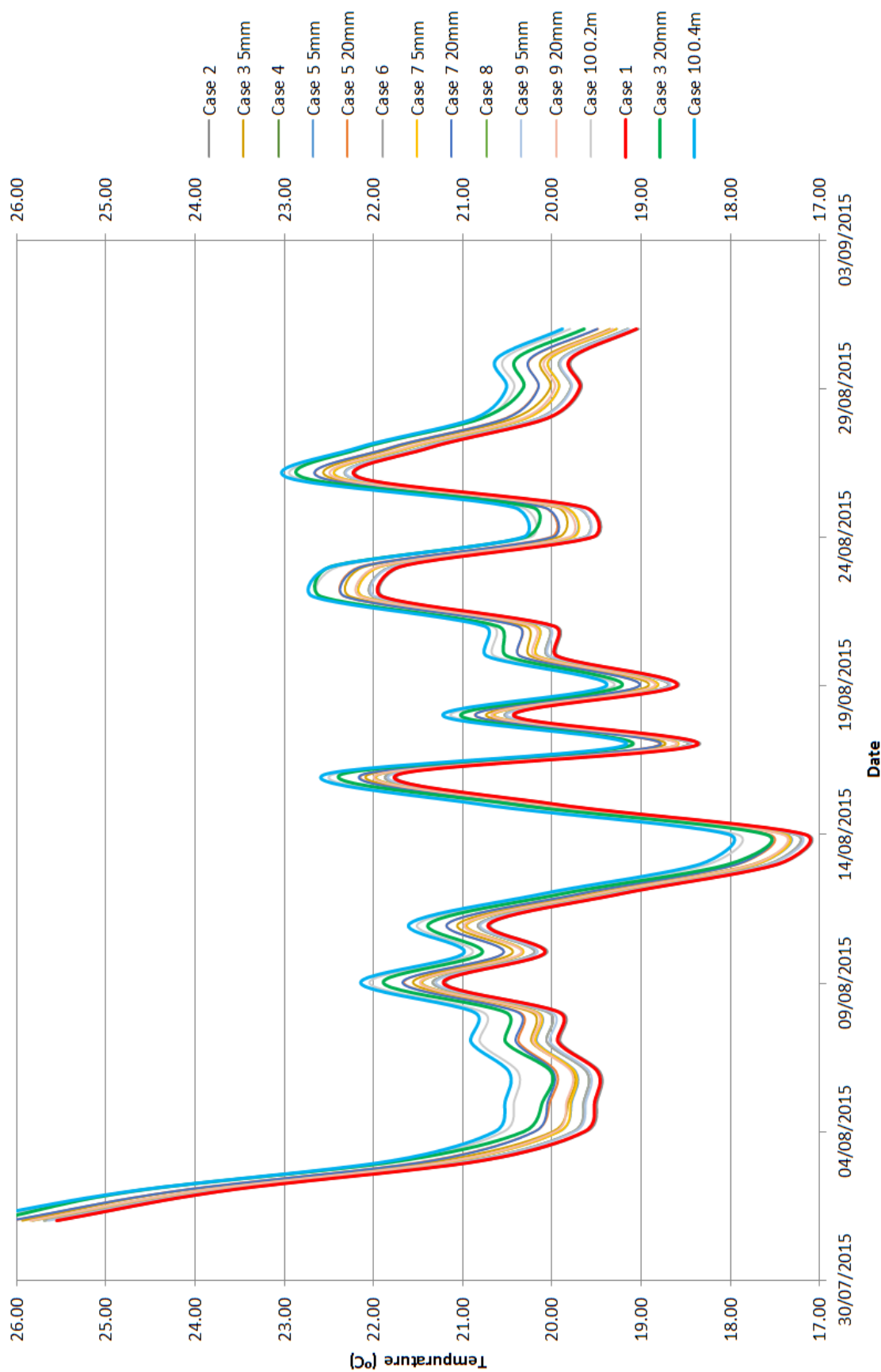
Temperature Plot for April with Case1, Case 3 20mm, and Case 10 0.4m highlighted

A5.3.2 West facing simulations

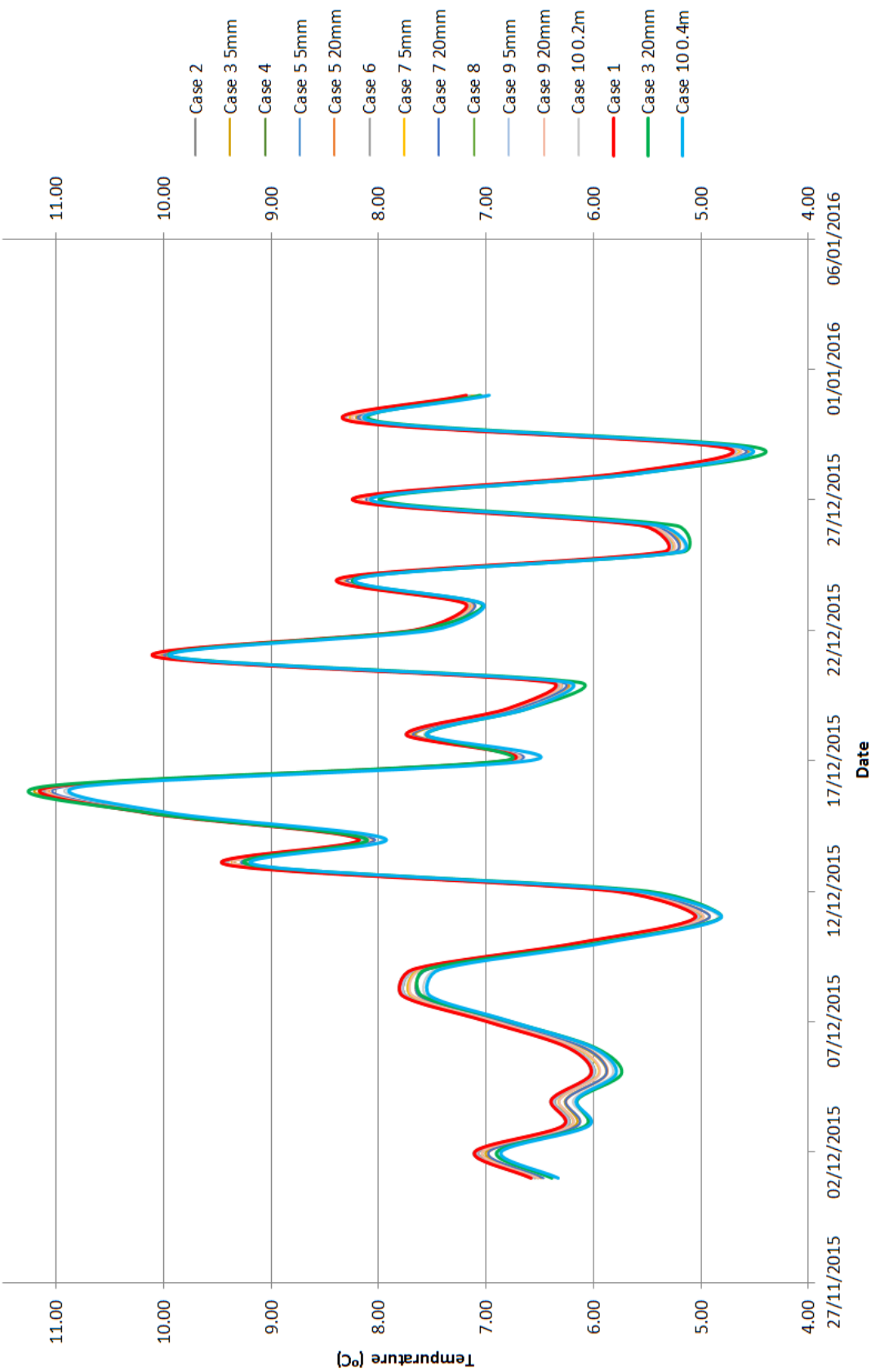




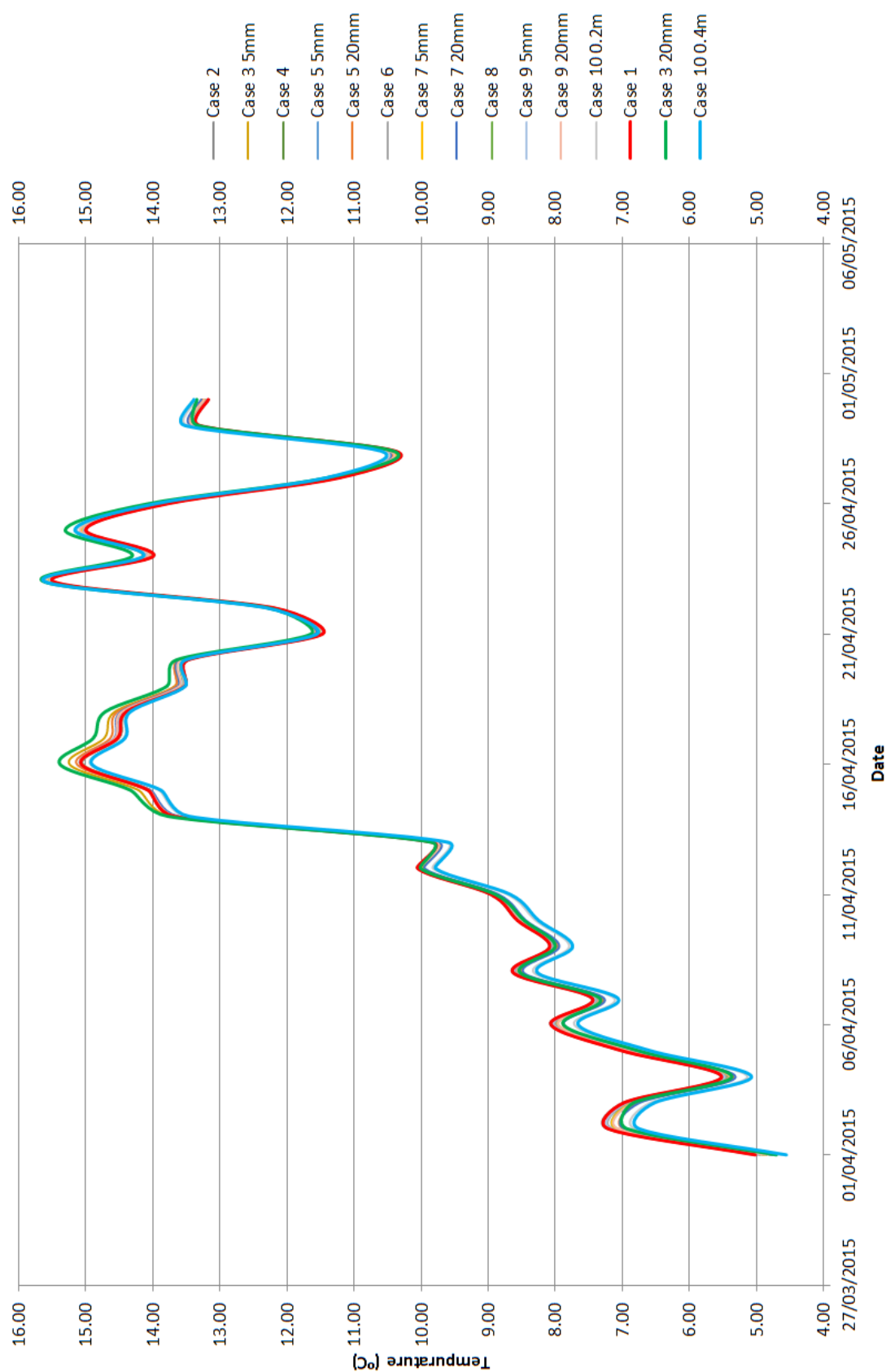
Style Temperature Comparison over 1 year



Temperature Plot for August with Case1, Case 3 20mm, and Case 10 0.4m highlighted

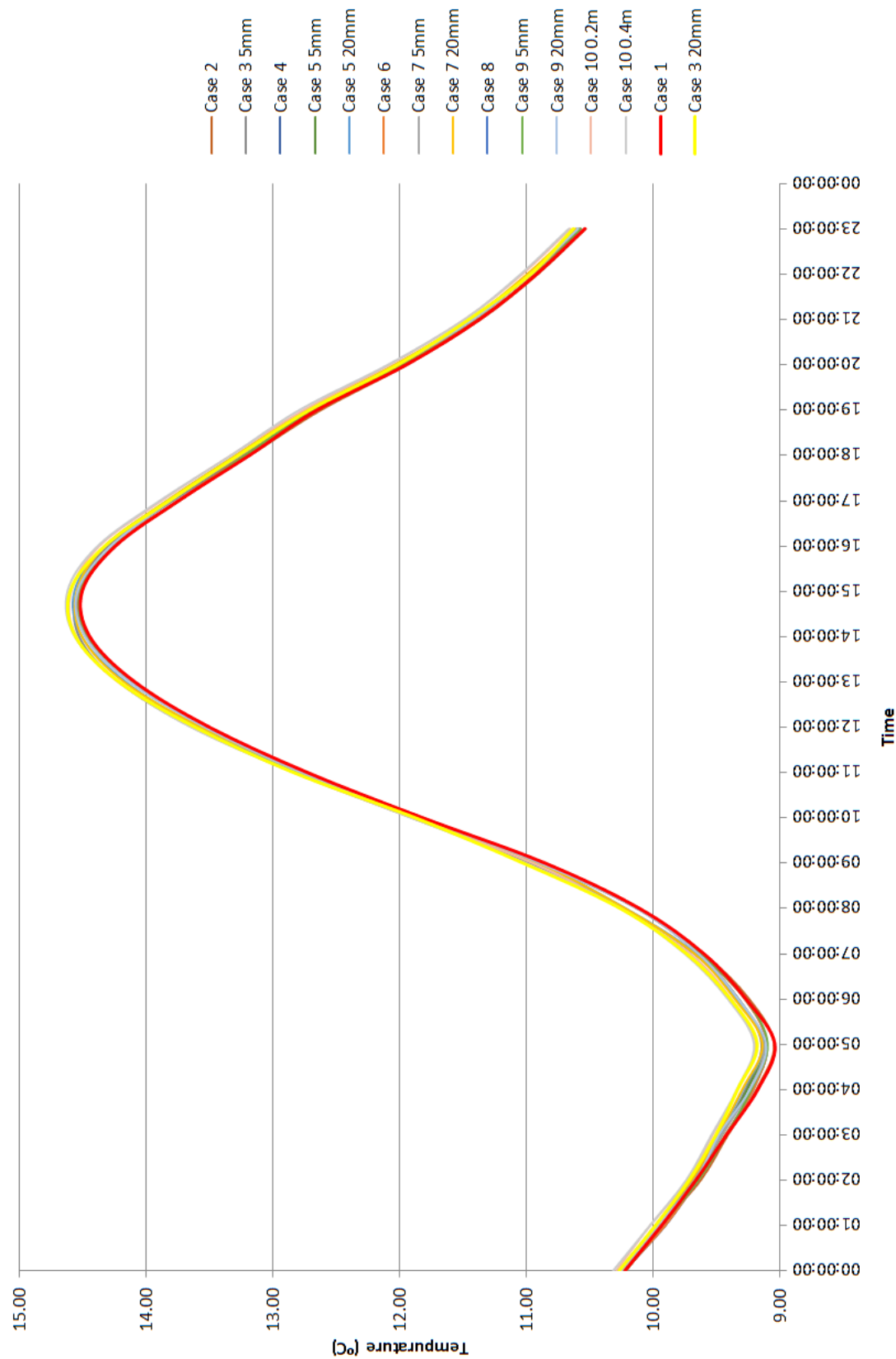


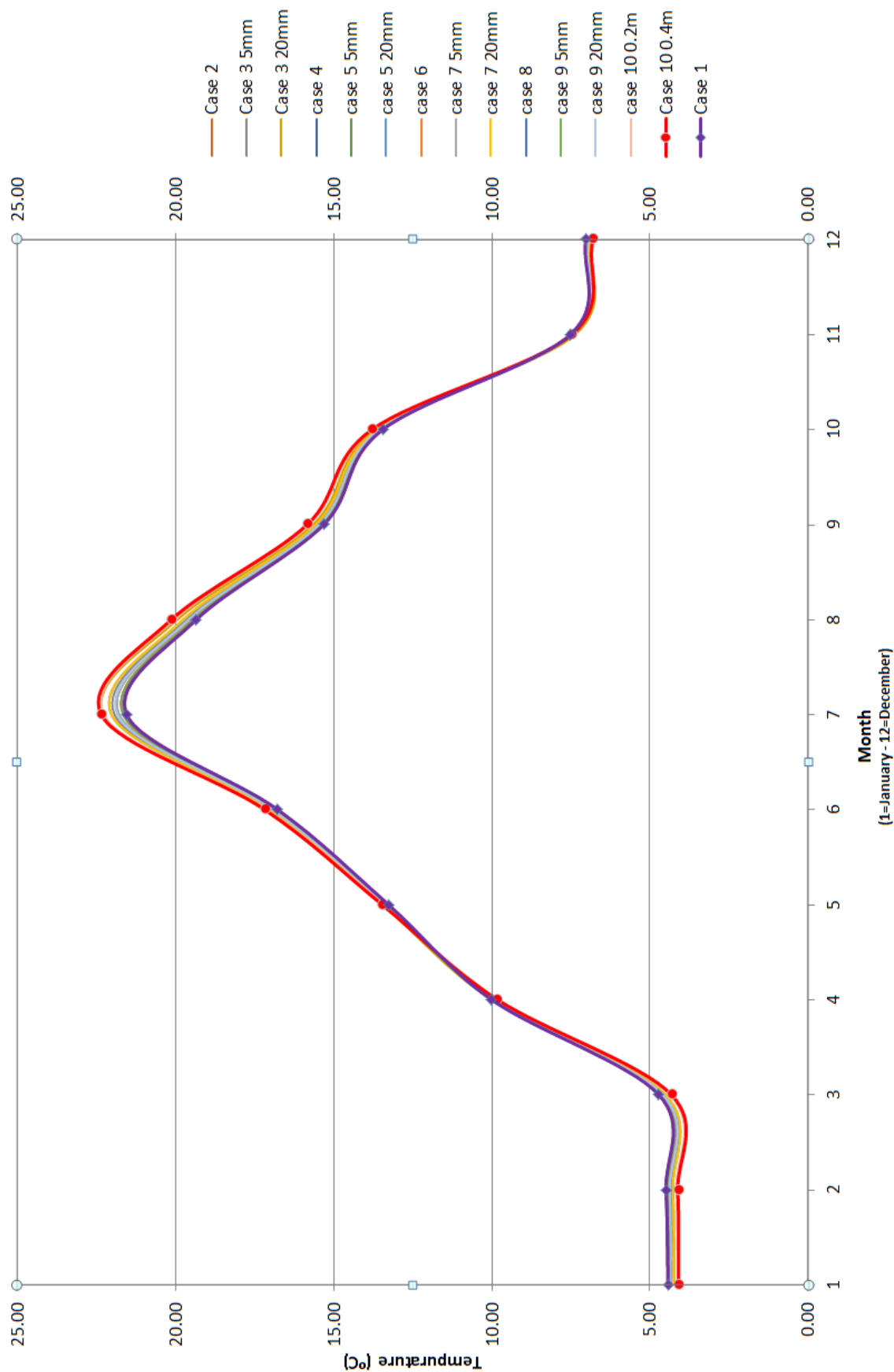
Temperature Plot for December with Case1, Case 3 20mm, and Case 10 0.4m highlighted



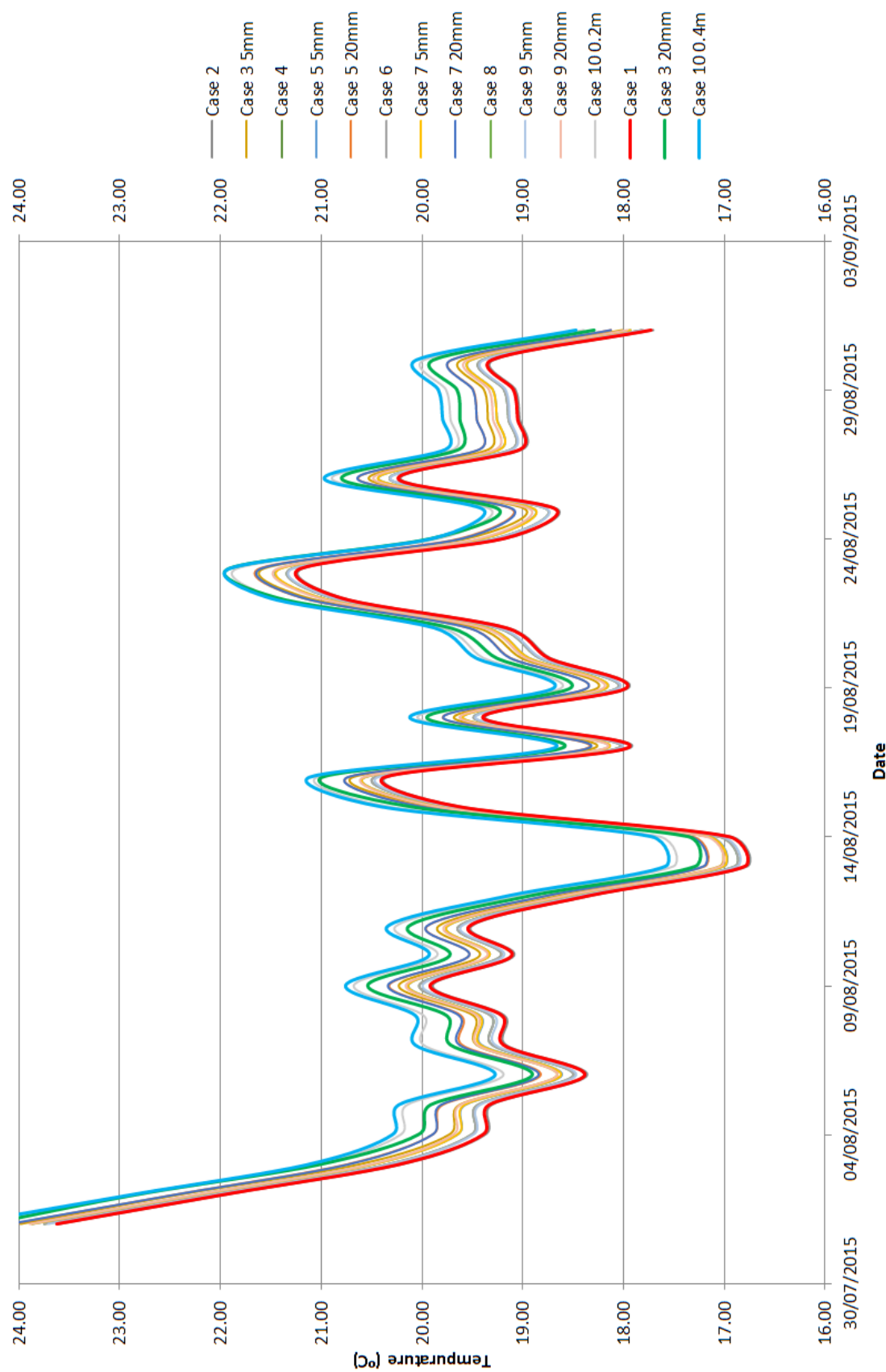
Temperature Plot for April with Case1, Case 3 20mm, and Case 10 0.4m highlighted

A5.3.3 North facing simulations

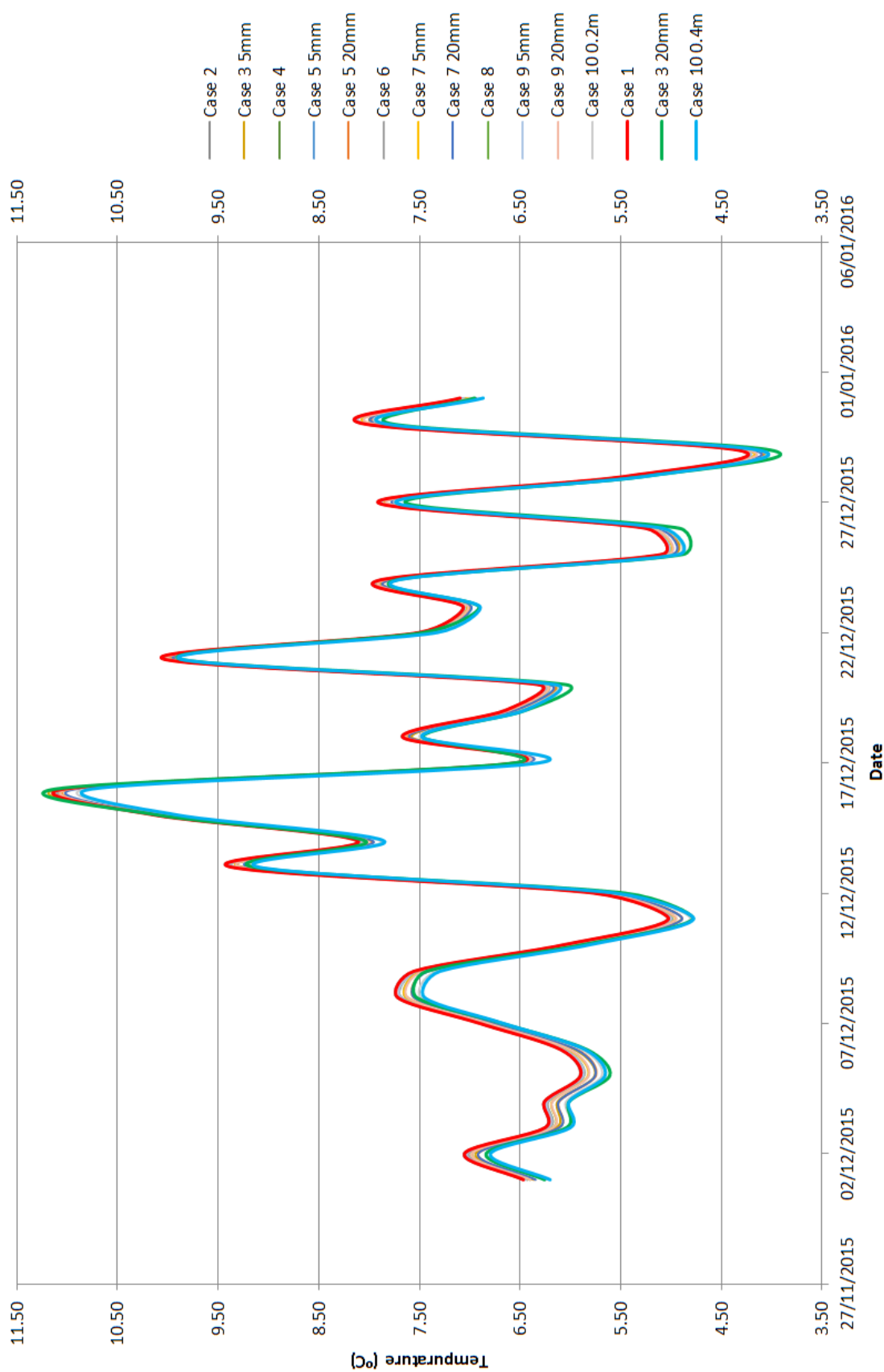




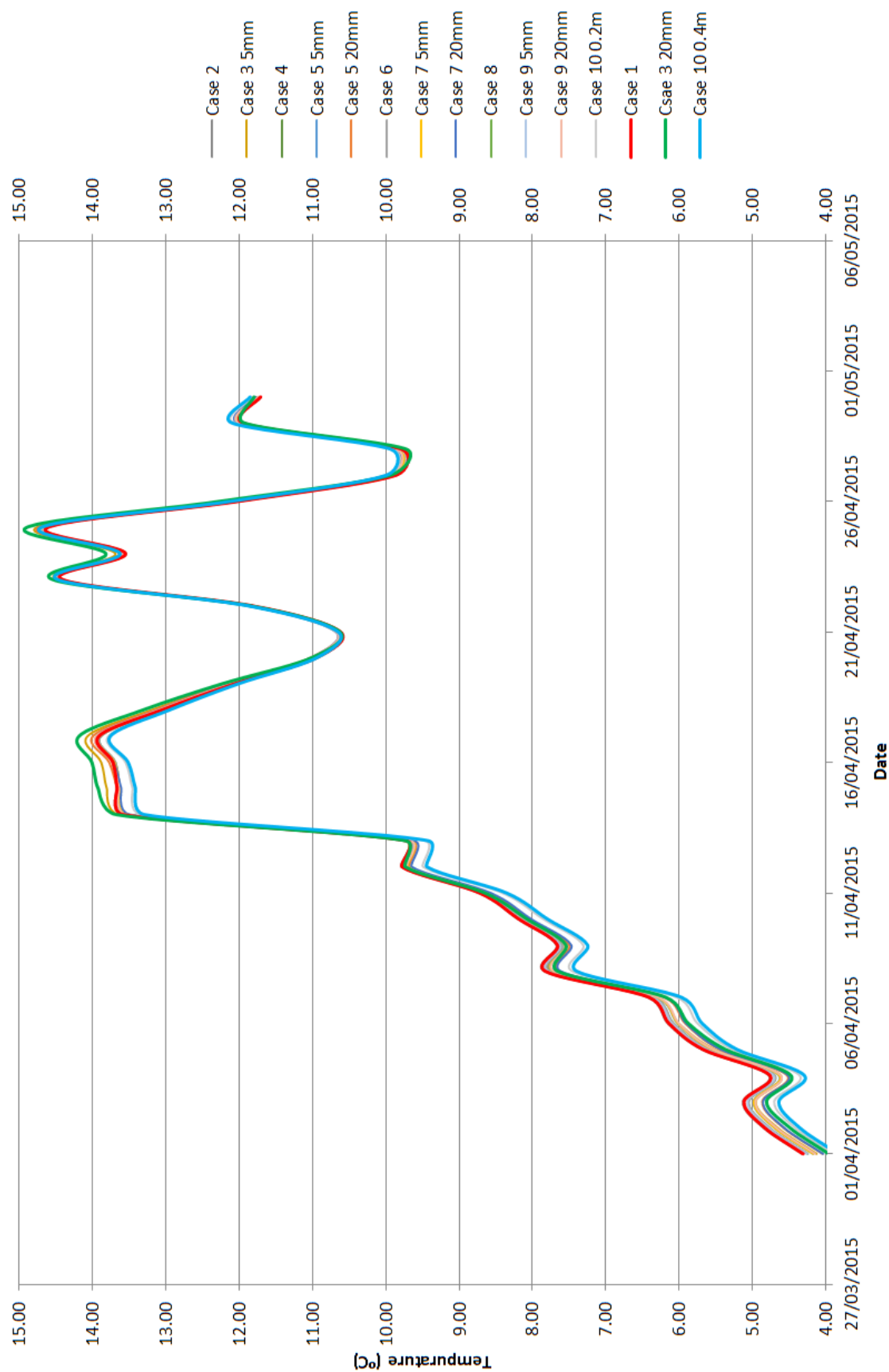
Style Temperature Comparison over 1 year



Temperature Plot for August with Case1, Case 3 20mm, and Case 10 0.4m highlighted



Temperature Plot for December with Case1, Case 3 20mm, and Case 10 0.4m highlighted



Temperature Plot for April with Case1, Case 3 20mm, and Case 10 0.4m highlighted